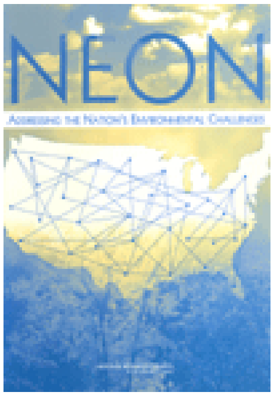

Neon: Addressing the Nation's Environmental Challenges

Committee on the National Ecological Observatory Network, National Research Council

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NEON

Addressing the Nation's Environmental Challenges

COMMITTEE ON THE NATIONAL ECOLOGICAL OBSERVATORY NETWORK

BOARD ON LIFE SCIENCES

DIVISION ON EARTH AND LIFE STUDIES

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Preface

The most complex systems that scientists have ever studied are biological, and of all biological systems perhaps none are more complex than natural and managed communities and ecosystems. A lake, forest, grassland, or marine habitat is likely to contain hundreds or even thousands of species of microscopic and macroscopic plants and animals and thousands of species of microorganisms, all interacting with each other in a physically and chemically complex and changing environment. During the last 3 decades, the scientific discipline of ecology has made large strides in understanding the fundamental processes that structure natural and managed communities and ecosystems. Those advances have come from the rigorous interplay of increasingly sophisticated experimentation, long-term observation, and mathematical (and increasingly mechanistic) theory.

Such scientific advances are coming none too soon; the last 3 decades have also been a period of accelerating and unprecedented human impacts on the species and ecosystems of the globe. Indeed, the consensus among environmental scientists is that humans have now dominated all natural processes combined as the major controllers of many of the regional, continental, and global forces and factors that determine ecological phenomena, from species abundances to the flow of goods and services of economic value to society.

However, because current ecological knowledge is based on studies of single sites and small subsets of the biodiversity of a site, it is unclear how applicable current results are to other regions and to other types of ecosystems. Major and fundamental scientific advances are needed if we are to have the requisite depth of knowledge for society to deal wisely with the environment.

Those concerns, which have been raised repeatedly in the discipline for the last decade, led the National Science Foundation (NSF) to propose the establishment of a National Ecological Observatory Network, or NEON. Building on the results of six workshops, NSF summarized the goal of NEON this way: "Collectively, the network of observatories will allow comprehensive, continental-scale experiments on ecological systems and will represent a virtual laboratory for research to obtain a predictive understanding of the environment." At the request of NSF, the National Research Council established an ad hoc committee to review and evaluate which major ecological and environmental issues and national concerns could be addressed only on a regional or continental scale, whether the current conceptualization of NEON was optimal to address them, and the impacts that NEON would have on science and society. Our committee was asked to prepare its report rapidly—as a 'fast track' report. I thank the committee members for their incredible willingness to put aside other important tasks as we spent our summer reading, holding two-day meetings, and reaching consensus, and then writing, discussing, and rewriting our report.

Throughout our deliberations, we kept our eyes on the big picture—on the major environmental challenges that the nation faces and on the most efficient and effective ways to obtain the scientific knowledge required to understand them and to deal with them wisely. We had neither the time nor the desire nor a charge to deal with all the assorted smaller details that will form an important part of NEON. Although we began with little knowledge of or personal participation in the earlier planning process for NEON, we grew to have a strong and unanimous support for the critical role that a NEON-like program could play both in the development of the discipline of ecology and in contributing to scientifically based environmental policy for the nation. Our environmental problems are regional to continental to global in scale. It is essential that our science be so, also.

G. David Tilman
Chair, Committee on the National Ecological Observatory Network

Acknowledgments

This report has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Dennis Baldocchi, University of California, Berkeley
Roger C. Bales, University of California, Merced
David Brakke, James Madison University
Joel Brown, University of Illinois, Chicago
Peter Daszak, University of Georgia

Michael Freeling, University of California, Berkeley
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Jerry Mahlman, National Center for Atmospheric Research
Thomas C. Malone, University of Maryland
Shahid Naeem, Columbia University
Michael D. Purugganan, North Carolina State University

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. May Berenbaum of the University of Illinois at Urbana-Champaign, and Dr. Frank Stillinger of Princeton University. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the author committee and the institution.

Contents

Executive Summary

Human technology, land use, and resource acquisition have accelerated the pace of regional and global environmental change to the extent that human actions are now a major force in the stability and functioning of most terrestrial, aquatic, and marine ecosystems. Those human-induced changes in our environment are expected to increase greatly over the coming decades, causing environmental issues to be one of the greatest challenges of the 21st century. The nation needs and deserves a scientific understanding of its natural and managed ecosystems that is sufficient to assess how alternative human actions might impact the functioning of ecosystems and the services that they provide the nation and to identify science-based solutions to ecological problems. Achieving the necessary mechanistic understanding of the environment, developing predictive ability and identifying solutions would require fundamental advances in basic scientific knowledge that can only be derived from a regional- or continental-scale program of experimental and observational research focused on the major environmental challenges that the nation faces.

The study of direct effects and feedbacks between environmental change and biological processes is inherently interdisciplinary and national in scope. Existing large-scale research programs, such as the National Atmospheric Deposition Program/National Trends Network, Global Energy and Water Cycle Experiments, and Moderate Resolution Imaging Spectroradiometer, have focused mostly on the physical and geochemical aspects of environmental change. To complement those programs, research should focus on the fundamental biological processes that underlie climate change and biogeochemical cycles and other important human-driven environmental change, such as introduction of invasive species, emerging diseases, and the loss of biodiversity. Research should synthesize population and ecosystem processes across regions with different environmental characteristics that influence ecological communities and across the continent. Biological research of such regional and continental scale has not been undertaken to any substantial extent, because of the inability of traditional small-scale ecological approaches to be scaled up to regional or continental scales. Indeed, neither the infrastructure required for such large-scale efforts nor the research efforts exist.

The National Ecological Observatory Network (NEON) proposed by the National Science Foundation (NSF) would be a network of infrastructure that would support continental-scale research on pressing environmental challenges. Major Research Equipment and Facilities Construction (MREFC) funding was requested to build a network for a coordinated, nationwide multisite network for experimental and observational environmental research. NEON would enable the study of common themes and the sharing of data and information across sites. It would facilitate a more integrated approach than merely linking existing research sites, such as the Long Term Ecological Research (LTER) sites, by allowing research on drivers of environmental changes to be pursued across the complete spectrum of ecosystems. It would be dedicated to producing the key results and fundamental scientific principles that are needed to project how human actions would likely affect natural and managed ecosystems across the nation in the coming decades.

PROCESS AND PURPOSE OF THIS STUDY

To evaluate the suitability of NEON to fulfill that role, NSF asked the National Research Council to convene an ad hoc committee to evaluate which major ecological and environmental issues and national concerns could be addressed only on a regional or continental scale, whether the current concept of NEON was optimal to address them, and what effects NEON would have on science and society (see Box ES-1).

The committee hosted a Web forum and a Web-casted workshop at which representatives of the Directorate for Biological Sciences, various relevant government agencies, and professional organizations spoke on NEON's potential. The broader scientific community was invited to post comments and views on the NEON Web forum. The committee also reviewed the reports of six NSF-supported workshops on NEON

Box ES-1
Statement of Task to the Committee on the National Ecological Observatory Network

1. What are the important issues in ecology and environmental biology that can only be addressed on a regional or continental scale? Are any of these issues of national concern?
2. Is a national network of field and laboratory research infrastructure (e.g., environmental sensor arrays, remotely operated gas and ion analyzers, biodiversity monitoring instrumentation) needed to address these questions?
3. Will NEON, as conceptualized in the series of six community workshops, be able to provide infrastructure and logistical support to address ecological and environmental questions of national concern?
4. What impact will NEON have on the scientific community and the next generation of scientists?

(NSF 2000 a,b,c, 2002 a,b,c), an American Institute for Biological Sciences report on NEON, and a variety of documents on NEON prepared by NSF, including its 2004 budget request to Congress. Information from all those sources was the basis of the committee's deliberations, which resulted in the conclusions summarized below.

CONCEPT AND POTENTIAL CONTRIBUTION OF THE NATIONAL ECOLOGICAL OBSERVATORY NETWORK

The committee felt that the vision of NEON, as developed by the scientific community in six workshops, was best articulated in two NSF statements: "collectively, the network of observatories will allow comprehensive, continental-scale experiments on ecological systems and will represent a virtual laboratory for research to obtain a predictive understanding of the environment" and "NEON will be focused around a very broadly based, general research question—what is the pace and nature of biological change. Individual observatories would have a broadly defined observatory-specific theme that would be consistent with this overarching NEON question."

The committee strongly endorses that vision as the central focus of NEON. In addition, the committee found strong support for NEON in other federal agencies, ecological scientific societies and organizations, and members of the scientific community. The committee did not address many of the minor differences and ambiguities that unavoidably arose when seven separate groups considered the diverse issues related to a potential NEON network

If NEON is implemented to fulfill that vision, the committee believes that it would be pivotal in addressing regional and continental questions of great scientific and social importance. NEON would facilitate coordinated research efforts by providing nationwide facilities for environmental biology that transcend the budget of a single university or consortium. The central goal of NEON should be to perform comprehensive, regional- to continental-scale experimental and observational research on the nation's natural and managed ecosystems to obtain an in-depth understanding of the environment in order to assess vulnerability and resilience of ecosystems to environmental changes. The resulting knowledge would allow the identification of how various alternative societal actions and policies would affect species and ecosystems, and would suggest remedies and solutions to environmental problems.

The major environmental challenges facing the nation that must be addressed by NEON result mostly from human actions that have regional, national, or global causes or effects. In the committee's view, the major ecological and environmental challenges that need to be addressed on a substantially expanded scale include the following:

- *Biodiversity, species composition, and ecosystem functioning.* Decreases in biodiversity and changes in species composition accompany most human uses of the biosphere. The loss of biodiversity can affect ecosystem functioning and ecosystem services of value to society. The loss of biodiversity and shifts in ecosystem composition range from local to continental scales, and thus must be studied on their natural scale if their national implications are to be understood.
- *Ecological aspects of biogeochemical cycle.* Humans are dominating natural processes as the major suppliers of the basic elements of life (carbon, nitrogen, phosphorus, and sulfur). The redistribution of those chemical elements, and human-produced toxins, on regional and continental scales may have profound effects on human health and on ecosystem function and stoichiometry, which may result in shifts in biodiversity, toxin accumulation, and concentration through the food chain.
- *Ecological implications of climate change.* Human-induced climate warming and variability strongly affect individual species, community structure and ecosystem functioning. Changes in vegetation in turn affect climate through their role in partitioning radiation and precipitation at the land surface. Climate-driven biological impacts are often only discernable at a regional-continental scale. Regional changes in ecosystem processes affect global water and carbon cycles. Therefore, a national approach to understanding biological response to climate variability and change is required.

- *Ecology and evolution of infectious diseases.* Exposure to and the dynamics, spread and control of emerging diseases and their effects on humans, crops, livestock, and wildlife require a new level of understanding. The majority of emerging infectious diseases in humans either utilize vectors such as mosquitoes or ticks, or are zoonotic diseases that are transmitted from wildlife. That will require knowledge of spatial variations in exposure, of the population dynamics of disease reservoirs, of the effects of pathogens on individual behavior, of the molecular basis of host-parasite interactions, and of the interactions with other pathogens and environmental threats.
- *Invasive species.* Invasive species affect virtually every ecosystem in the United States, and can cause substantial economic and biological damage. The identification of potentially harmful invasive species, the early detection of new species as invasion begins, and the knowledge base needed to prevent their spread require a comprehensive monitoring and experimental network and a mechanistic understanding of the interplay of invader, ecosystem traits and other factors including climate and land use that determine invasiveness.
- *Land use and habitat alteration.* Deforestation, suburbanization, road construction, agriculture, and other human land-use activities cause changes in ecosystems. Those changes modify water, energy and material balances and the ability of the biotic community to respond to and recover from stress and disturbance. Actions in one location, such as farming practices in the upper Midwest, can affect areas 1,000 or more miles away because areas are joined by water and nutrient flow in rivers and by atmospheric transport of agrochemicals.

The committee listed the six issues in alphabetical order and did not attempt to prioritize them in any way. These ecological and environmental issues have been studied on a local scale, but results from those studies are confined by their spatial scale and cannot be extrapolated to address national concerns. The committee concluded that a comprehensive understanding of those environmental issues can only be achieved through regional to continental scale research using a national network of experimental and observational research infrastructure. Although the committee acknowledges that there are other ecological and environmental issues that can be addressed only on an expanded spatial scale, it suggests those six issues because of their immediate importance. Because the six issues presented above are interrelated at many levels, they present many opportunities for research integration and for sharing resources.

The 20th century saw many threats to the environmental health of the nation, such as decreasing water availability and deteriorating water quality, spread of invasive species and emerging infectious diseases (for example, West Nile virus), and extinction of valued species, some of which are new and emerging while others have been persisting for a long time. Current responses to environmental problems are mostly attempts to reverse the adverse trends because we lack a comprehensive understanding of the source of problems. Such an understanding can only be achieved though multiscale research that combines experimentation and observation replicated at numerous sites across the nation. A network of nationwide infrastructure, such as NEON, would enable local to regional to continental scale environmental research that would otherwise be impractical or impossible due to logistical constraints. Thus, studies at NEON would allow environmental scientists and biologists to be active in mitigating large-scale adverse impacts before they become severe threats to society. The scientific advances made possible by NEON would allow forecasting of the effects of alternative environmental policies and actions. Environmental forecasting is crucial for determining the net costs and benefits of alternative policies and thereby helping society to choose policies that provide the greatest long-term net benefits.

The committee strongly supports the creation of a NEON-like program and commends NSF's overall vision for NEON. However, it feels that the proposed implementation plans need modification and refinement to ensure that NEON would focus on the most important scientific issues, efficiently provide the national network of infrastructure essential for each challenge, encourage creative research, and meet the requirements of MREFC funding. First, in NSF's current plan, a NEON network would be built gradually via funding of one or two regional observatories at a time. Thus, NEON would not be a truly national network of sites until all the observatories are funded and built, which could take more than a decade. Second, the formulation and implementation of each regional observatory would be driven mostly by responses to requests for proposals. Institutions or consortia would submit proposals with their ideas of design and implementation to compete for a contract to build and operate a NEON observatory with a proposed budget of $20 million for construction and $3 million for maintenance. That approach has the great advantage of encouraging creativity and investigator dedication, but it would decrease the ability of NEON to address major environmental challenges in a coordinated regional to national manner. Moreover, NSF's current approach does not provide the committee or Congress with a clear idea of what each NEON observatory would look like or do. Detailed design and implementation plan is often required to obtain MREFC funding.

To establish a coordinated, efficient, and truly nationwide network, the committee suggests that NSF structure NEON according to the environmental challenges to be addressed rather than by locating one site in each ecosystem type represented in the United States. Thus, NEON would consist of a total of six "observatories" (rather than 17), one for each of the six environmental challenges. Each observatory would consist of multiple sites chosen simultaneously and located strategically across the nation to ensure adequate regional and national coverage for addressing the challenge. The funding needed to set up and maintain each of the six observatories would depend on its specific focus and plans, and the costs for an observatory might substantially exceed the $20 million for construction and $3 million for annual maintenance that NSF estimated for its original concept of a network of 17 regional observatories. The total costs for six national rather than 17 regional observatories might, however, be comparable with or less than costs for the original concept, particularly because infrastructure for research on more than one of the six themes could be colocated at many sites. Most important, sufficient funds should be allocated to ensure that each observatory is a truly nationwide network. Specific research projects conducted at individual sites within a NEON observatory should be funded through other NSF research, rather than infrastructure, programs.

Second, the committee believes that NEON observatories could contribute to and potentially unify relevant environmental data that are being gathered by other federal, state and local agencies. Moreover, particular NEON observatories could build on existing NSF research sites (LTER sites), the Department of Energy's programs (Free-Air Carbon Dioxide Enrichment experiments and AmeriFlux eddy flux towers), and other projects. The committee supports NSF's effort to have NEON observatories form partnerships with other federal, state, and local agencies and suggests formulation of plans to address such issues as standardization of protocols and data and coordination of research.

NEON programs would be ideal location for undergraduate and graduate interdisciplinary training and for K-12 students and teachers to study science on the basis of observation and experimental inquiry. The integration of research, education, and public outreach should be a central feature of NEON, and educational and outreach plans should be included from the inception of each observatory.

FINDINGS AND RECOMMENDATIONS

On the basis of its analyses, many of which were summarized above, the committee strongly endorses a NEON-like endeavor and the broad vision of NEON's mission that NSF articulated in the opening sentences of its 2004 congressional budget request. We offer the following findings and broad recommendations to help NEON to achieve its goals.

Finding 1

The committee identified six critical environmental challenges that are regional, continental, or global in their extent—biodiversity, species composition, and ecosystem functioning; ecological aspects of biogeochemical cycles; ecological implications of climate change; ecology and evolution of infectious diseases; invasive species; and land use and habitat alteration. Although all six issues are of national concern, at present we do not have knowledge adequate to address them. Rapid and substantial advances in basic scientific knowledge would be needed for society to deal with those major environmental issues wisely.

Recommendation 1

The committee strongly recommends that the nation and NSF give highest priority to research on the six environmental challenges the committee identified.

Finding 2

An in-depth understanding of the causes and consequences of the six challenges is needed to allow assessment of potential ecosystem responses and to formulate effective environmental policy. Meeting this need would require large-scale experimentation, long-term observation, and scientific synthesis that could be carried out only using a network of nationwide infrastructure and research sites that are optimized for the purpose.

Recommendation 2

The committee strongly endorses a NEON-like endeavor and the vision of the mission of NEON that NSF has articulated. As proposed by NSF, the central goal of NEON would be to perform comprehensive, regional- and continental-scale experimental and observational research on the nation's ecological systems to obtain an in-depth understanding of the environment. That knowledge could serve as a basis for developing predictive capability and would allow assessment of how alternative societal actions and policies will affect species and ecosystems and the services that they provide to society.

Finding 3

NEON, as currently proposed, would be built piecemeal via funding of one or two regional observatories at a time, and each observatory would be managed by a different university or consortium. Such a design and implementation might hinder the integration and the national nature of the network of sites and make it less than optimally effective in facilitating coordinated regional- and continental-scale research.

Recommendation 3

Each NEON observatory should be initiated as a nationwide network of facilities and infrastructure designed by a coalition of many multi-investigator, multi-disciplinary teams from across the nation to address optimally one of the six major environmental challenges. Each observatory should accommodate a combination of experimentation and observation and should comprise a collection of nationwide sites—whether terrestrial, freshwater, or marine—that are most relevant to its central theme. Sufficient funds must be allocated for the development of each NEON observatory as a nationwide network. Because the six research themes identified by the committee have overlapping infrastructure needs, construction of each new observatory could successively build on sites and infrastructure of existing observatories. Each later observatory could leverage investments made in the existing ones; this would increase the effectiveness and decrease the cost of the entire network.

Finding 4

The committee agrees with the fundamental concept of NEON as stated by NSF and with many of the major recommendations derived from the six workshops. It believes that NEON would provide opportunities for large-scale environmental research and enable intellectual and scientific development that is impossible with existing infrastructure. However, the effective implementation of NEON and the maximization of its contributions to science and the nation require a refined focus and a more detailed plan for its implementation.

Recommendation 4

The creation of a NEON observatory addressing one of the six major environmental challenges would probably be a multistep process involving open workshops and working groups on that challenge, peer-reviewed preproposals submitted by different teams for work on that challenge at particular sites, and discussion and coordination among the chosen teams to synthesize the diverse ideas generated and create final plans for the entire observatory. The goals of the multistep process are to optimize the ability of various scientists to contribute creativity and personal commitment to the observatory and the ability of the multiple teams and sites to pursue their shared challenge in a coordinated manner. The result would be a clear vision of what the observatories are intended to look like and achieve, which would additionally provide a better fit within the purview of Major Research Equipment and Facilities Construction funding. The committee offers some specific suggestions:

- NSF should encourage NEON observatories to form partnerships with existing informatics centers (for example, the National Center for Ecological Analysis and Synthesis, the National Biological Information Infrastructure and GenBank) or use them as models.
- Each NEON observatory should form partnerships with appropriate federal, state, and local agencies and organizations to coordinate and optimize data collection and sharing. Establishing memoranda of understanding could facilitate partnerships and collaboration.
- The committee endorses NSF's proposal of a coordinating unit to oversee the implementation and operation of NEON. It recommends that a single scientific oversight committee, preferably formed by a neutral body such as a multiuniversity consortium, provide this oversight.

Finding 5

The challenge of educating the next generation of scientists, teachers, and students and of reaching out to the public about environmental science and issues cannot be met casually by individual researchers. Nothing short of an integrated, sequenced education and outreach plan that meets national standards, targets audience needs, and is based on measurable outcomes will answer the leadership and education vision set forth to NSF by the National Science Board. The NEON observatories are ideal venues for such an integrated, robust education and outreach plan.

Recommendation 5

NEON's education programs should be targeted at undergraduate and graduate students and faculty, precollege students and teachers, and informal education, and citizen outreach. We recommend that multiple, systematic programs be integrated into the NEON proposal and developed, sequenced, and planned beginning at each observatory's inception and with attendant funding mechanisms and budgets.

If implemented in the general format outlined above, NEON could provide the fundamental scientific advances needed to understand how human-induced environmental change influences the long-term quality of life and wealth creation for the nation. Long-term outputs would include a science-based approach to environmental policy, risk analysis for environmental threats, evaluation of potential approaches to the threats, and a venue for increasing public awareness and understanding of environmental issues. NEON could revolutionize the discipline of environmental biology by transforming ecology into a more mechanistic science that generates predictions and solutions that would help society to deal actively with major environmental issues.

CHAPTER ONE

The National Ecological Observatory Network

This chapter describes the original concept of the National Ecological Observatory Network as envisioned by the National Science Foundation. Funding from the Major Research Equipment and Facilities Construction account and the objectives of this report are also presented.

The discipline of ecology has made great strides in the last 50 years. The field has moved from early studies of individual plant and animal species and their interactions to such work as exploring the effects of interactions among multiple hosts and vectors on the dynamics of emerging diseases and exploring the effects of exotic species, climate change, loss of biodiversity, and other components of environmental change on ecosystem structure and functioning. Given the recent recognition that environmental changes are occurring on regional to continental and global scales, geographic extent and time scales of ecological research are now necessarily expanding. Such efforts as the National Science Foundation (NSF) Long-Term Ecological Research (LTER) program are allowing investigation of individual ecosystems and their component organisms and processes over long periods. LTER focuses on site-specific ecological research but major advances in the understanding of ecological systems and environmental change will require research that is substantially expanded to encompass regional and continental scales. New knowledge and technology from molecular biology and genetics now allow study of organisms (such as bacterial and viral pathogens and soil bacteria and fungi) and processes (such as rapid evolution of disease virulence when emerging diseases switch host species) that are central components of environmental change. During the last decade, ecologists have increasingly recognized the need for their discipline to greatly expand the spatial scope of its research (NSB 2000), to focus on major environmental problems (Lubchenco et al. 1991, Vitousek 1994, NRC 2001), and to develop an understanding deep enough to allow predictions of how ecological processes would be affected by alternative policies and actions (Clark et al. 2001). In response to those needs and with advice from six workshops, NSF developed the concept of the National Ecological Observatory Network (NEON).

THE NATIONAL ECOLOGICAL OBSERVATORY NETWORK AS ENVISIONED BY THE NATIONAL SCIENCE FOUNDATION

The vision of NEON as presented to the committee by NSF personnel was best summarized in two statements: "Collectively, the network of observatories will allow comprehensive, continental-scale experiments on ecological systems and will represent a virtual laboratory for research to obtain a predictive understanding of the environment" (NSF 2004 budget request to Congress, <http://www.neon/nsf.gov/bio/bio_bdg04/neon04.htm>) and "NEON will be focused around a very broadly based, general research question—what is the pace and nature of biological change? Individual observatories would have a broadly defined observatory-specific theme that would be consistent with this overarching NEON question" (NSF 2000c).

NSF outlined these objectives of NEON (<http://www.nsf.gov/bio/neon/faqs.htm#one>)

- To provide a state-of-the-art national facility for scientists and engineers to conduct cutting edge research spanning all levels of biological organization from molecular genetics to whole ecosystem studies and across scales ranging from seconds to geological time and from microns to kilometers.

- To interconnect the geographically distributed parts of the facility into one virtual installation via communication networks so that members of the field biology research community can access the facility remotely.
- To facilitate predictive modeling of biological systems via data sharing and synthesis efforts by users of the facility.

NEON would provide a national network of infrastructure that could be used by a large number of biological, physical, and social scientists to achieve a better understanding of our nation's ecosystems. The information obtained through NEON would help local, state, and federal policy-makers to make informed decisions. Furthermore, NEON information and facilities can serve as tools for K-12 and college education.

NEON has no parallel in current research for environmental biology in the United States. The infrastructure of NEON would uniquely allow research on the geographic scale demanded by current environmental problems. Through the network of facilities built to conduct detailed ecological experiments and observations related to major environmental issues, the biological effects of alternative environmental actions and policies could be forecasted and evaluated.

Design of NEON

NSF envisions NEON as a network of observatories, each of which is itself a network of field sites in a region (Figure 1-1). Each regional observatory will comprise a "core site" that is linked to a series of inter-connected "satellite sites" through high-speed Internet. The sites in each observatory will collectively provide the necessary breadth and depth of field facilities, research infrastructure, and analytical capability for comprehensive state-of-the-art research in field biology.

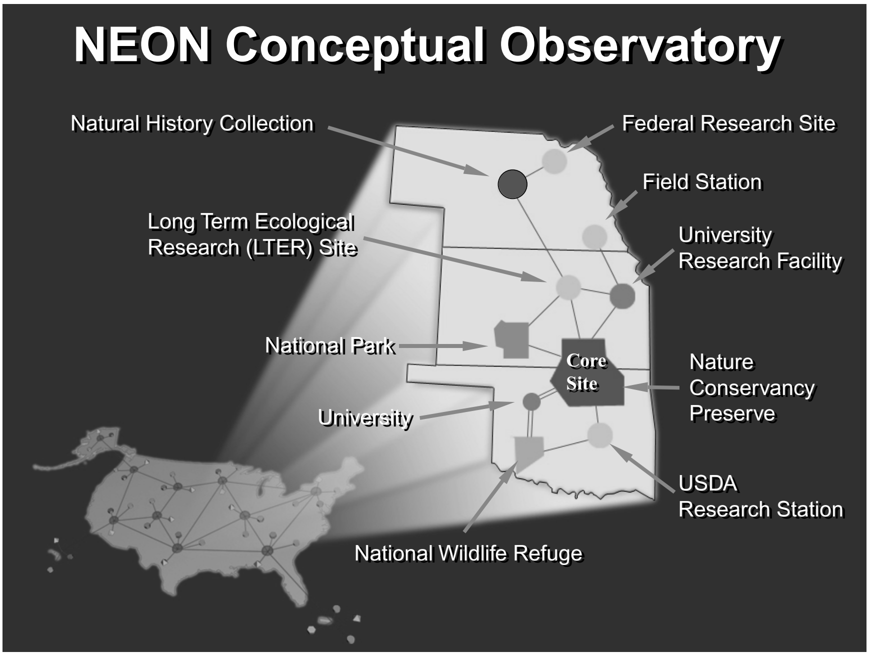

FIGURE 1-1 Example of possible NEON observatory, showing partners, sites, and facilities potentially linked to form a regional footprint. SOURCE: NSF 2002d.

The core sites will be heavily instrumented and intensive, specialized research infrastructure will be deployed to maximize the capability of data collection, processing, and analysis. Satellite sites will contain various amounts of field instrumentation and thus have different degrees of research capabilities. The core and satellite sites will collectively cover an array of ecotypes within a region. The sites could consist of existing biological field stations, LTER sites, marine laboratories, university facilities, or federal, state, or local agency research facilities. The aims of the regional networks of research sites are to leverage existing infra-structure and to encourage and facilitate partnerships among government agencies, academic institutions, and others. Although exact locations of the observatories will be selected by open competition through peer review, the complete NEON network is envisioned as encompassing all the major biomes with replicated study sites within and across regions.

Coordination of NEON

Because coordination of research efforts and standardization of methods and data would be keys to the success of a network like NEON, NSF proposes a NEON coordinating unit to manage the integration of the observatories. The NEON coordinating unit would develop and implement plans for core equipment, core data measurements, data quality and control standards, information-management standards and practices, and data-accessibility policies. In addition, the unit would integrate NEON activities with each other and with existing federal, state, and local programs and would coordinate public outreach activities.

Because NSF suggests that NEON activities be integrated with existing federal, state and local programs, the American Institute of Biological Sciences is developing a database of current federal and state field-based ecological programs with an eye to facilitating the establishment of connections between academic researchers and existing government programs. The database used by the Heinz Center for its report *The State of the Nation's Ecosystems: Measuring the Lands, Waters, and Living Resources of the United States* would also be useful in that regard.

MAJOR RESEARCH EQUIPMENT AND FACILITIES CONSTRUCTION ACCOUNT

In FY 2003, NSF requested that Congress allocate $12 million to the Major Research Equipment and Facilities Construction (MREFC) account to initiate construction of the first two NEON observatories (<http://www.nsf.gov/bio/bio_bdg04/neon04.htm>). That was the first time that NSF had sought congressional allocation of MREFC funds in support of biological research. Another $12 million from the MREFC account was requested in FY 2004 to continue construction of the two observatories. In addition, NSF requested congressional approval of

$6.0 million in FY 2004 from the Research and Related Activities (R&RA) account to support operation and management of the first two NEON sites. To date, Congress has not approved any of the requests for NEON funding but rather has denied them "without prejudice."

The MREFC account is a separate line item in the NSF budget that provides NSF with an agency-wide mechanism to allow directorates to propose and undertake large-facility projects costing tens to hundreds of millions of dollars. MREFC funds support acquisition and construction not only of single-purpose large facilities and large-infrastructure projects, but also of national networks that affect research communities. The R&RA account supports construction of less-expensive facilities and other activities, such as planning, design, development, operation, and maintenance (NSF 2002e).

Examples of single-purpose large facilities and large infrastructure that have been supported through MREFC funds are the Atacama Large Millimeter Array—the world's largest and most powerful radio telescope operating at millimeter and submillimeter wavelengths; the High Performance Instrumented Airborne Platform for Environmental Research, a research aircraft with altitude, range, and endurance capabilities that would enable investigators to perform critical earth system research, and the Laser Interferometer Gravitational Wave Observatory, two sites that consist of L-shaped interferometers designed to detect gravitational waves. MREFC funds have also been used to fund network projects like NEON. For example, EarthScope is a network of multipurpose geophysical instruments and observatories that substantially expand capabilities to observe the geophysical structure and deformation of North America.

According to NSF guidelines, the usual life cycle of an MREFC project can be described in five stages: concept, development, implementation, operation and maintenance, and renewal or termination (NSF 2002e). During the concept stage, the scientific community defines the need for the facility and infrastructure to make progress in a particular discipline. The need for the project must be articulated in the context of existing or planned resources in the discipline, opportunities that would be forgone if the project were not undertaken, and its effect on the balance and concentration of research and education in the discipline. The project must be well supported by relevant scientific and education communities, have potential beneficial effect on education and training, exploit potential partnerships fully, and be scaled and operated to match the stated research and education goals and objectives. If the project meets those criteria, its concept will be developed through workshops or study committees. The potential for partnerships should be fully and actively explored in the planning process so that NSF and partner agencies can establish their mutual interests and potential cost-sharing. The conceptual plan should include design, cost, schedule and performance goals and a vision of the development, implementation, and operation and maintenance of the facility and infrastructure. If the plan is approved by the assistant director/office head at NSF, the project can proceed to the development stage and will be included in the running list of MREFC projects that are submitted for consideration by Congress.

PROCESS AND PURPOSE OF THIS STUDY

To evaluate the suitability of NEON to fulfill this role, NSF asked the National Research Council to convene a committee to deliberate on which ecological and environmental issues can be addressed only on a regional or continental scale and whether NEON would be the optimal network of infrastructure to address them (see Appendix A for committee membership). The committee was charged to answer these questions:

- What are the important issues in ecology and environmental biology that can only be addressed on a regional or continental scale? Are any of these issues of national concern?
- Is a national network of field and laboratory research infrastructure (e.g., environmental sensor arrays, remotely operated gas and ion analyzers, biodiversity monitoring instrumentation) needed to address these questions?
- Will NEON, as conceptualized in the series of six community

workshops, be able to provide infrastructure and logistical support to address ecological and environmental questions of national concern?

- What impact will NEON have on the scientific community and the next generation of scientists?

To gather input for its study, the committee hosted a public workshop on June 9, 2003 (see Appendix B for workshop agenda). Representatives of the NSF Directorate for Biological Sciences were invited to present NSF's vision for NEON and to address queries about NEON from the committee and the audience. Various relevant government agencies and professional organizations were also invited to be represented at the workshop. In addition to the workshop, the National Research Council hosted a Web forum from June 2 to 17, 2003, during which the broad scientific community was invited to post comments and views on NEON. The committee used input gathered from the workshop and Web forum, printed documents on NEON, and its members' own expertise and experience in its deliberations.

CHAPTER TWO

Environmental Issues of National Importance and the Role of the National Ecological Observatory Network

The committee examined and identified the main environmental challenges facing the nation. This chapter also discusses the importance of developing education programs in environmental science for the general public and the next generation of scientists.

Ecological and environmental research has traditionally been dominated by projects of single investigators or small groups working on local scales. However, environmental change and its influence on biological processes occur on regional, continental, and global scales. We define a region on the basis of environmental characteristics that influence biology, such as climate and precipitation (subtropical Florida vs. the desert), terrain (the Rocky Mountains vs. the Great Plains), and the presence and absence of extensive watersheds (the Great Lakes region). We use the term continental to describe transcontinental processes. Although there are a few continentwide environmental monitoring programs—Global Energy and Water Cycle Experiments, National Atmospheric Deposition Program/National Trends Network, Moderate-Resolution Imaging Spectroradiometer, and so on—those programs rarely link physical environmental changes to biological processes. To adequately study the sources of and seek solutions for environmental problems on this expanded range of scales, information on physical and geochemical processes should be complemented by biological studies. Furthermore, biological studies must be conducted at the appropriate time and spatial scales to ensure that experimental results are applicable to natural systems and processes (Gardner et al. 2001).

After considering the numerous environmental issues that the nation faces, the committee is in general agreement with the conclusions of the NRC report *on Grand Challenges in Environmental Sciences* (NRC 2001). In particular, the committee identified six major environmental challenges for which a NEON-like national network of infrastructure would be essential for their solution. The challenges are to develop an increased understanding, via improved observations, focused experimentation and the development and testing of mechanistic theory of the following pressing environmental issues:

- *Biodiversity, species composition, and ecosystem functioning.* Decreases in biodiversity and changes in species composition accompany most human uses of the biosphere. The loss of biodiversity can affect ecosystem functioning and ecosystem services of value to society. The loss of biodiversity and shifts in ecosystem composition range from local to continental scales, and thus must be studied on their natural scale if their national implications are to be understood.
- *Ecological aspects of biogeochemical cycle.* Humans are dominating natural processes as the major suppliers of the basic elements of life (carbon, nitrogen, phosphorus, and sulfur). The redistribution of those chemical elements, and human-produced toxins, on regional and continental scales may have profound effects on human health and on ecosystem function and stoichiometry, which may result in shifts in biodiversity, toxin accumulation, and concentration through the food chain.
- *Ecological implications of climate change.* Human-induced climate warming and variability strongly affect individual species, community structure and ecosystem functioning. Changes in vegetation in turn affect climate through their role in partitioning radiation and precipitation at

the land surface. Climate-driven biological impacts are often only discernable at a regional-continental scale. Regional changes in ecosystem processes affect global water and carbon cycles. Therefore, a national approach to understanding biological response to climate variability and change is required.

- *Ecology and evolution of infectious diseases.* Exposure to and the dynamics, spread and control of emerging diseases and their effects on humans, crops, livestock, and wildlife require a new level of understanding. The majority of emerging infectious diseases in humans either utilize vectors such as mosquitoes or ticks, or are zoonotic diseases that are transmitted from wildlife. That will require knowledge of spatial variations in exposure, of the population dynamics of disease reservoirs, of the effects of pathogens on individual behavior, of the molecular basis of host-parasite interactions, and of the interactions with other pathogens and environmental threats.
- *Invasive species.* Invasive species affect virtually every ecosystem in the United States, and can cause substantial economic and biological damage. The identification of potentially harmful invasive species, the early detection of new species as invasion begins, and the knowledge base needed to prevent their spread require a comprehensive monitoring and experimental network and a mechanistic understanding of the interplay of invader, ecosystem traits and other factors including climate and land use that determine invasiveness.
- *Land use and habitat alteration.* Deforestation, suburbanization, road construction, agriculture, and other human land-use activities cause changes in ecosystems. Those changes modify water, energy and material balances and the ability of the biotic community to respond to and recover from stress and disturbance. Actions in one location, such as farming practices in the upper Midwest, can affect areas 1,000 or more miles away because areas are joined by water and nutrient flow in rivers and by atmospheric transport of agrochemicals.

Each of these six environmental challenges is a source of effects in human social and economic systems, as well as in the nation's ecosystems.

Environmental sustainability and livability depend heavily on natural resource use and other human behaviors. The environment is "the critical infrastructure without which neither an economy nor a society can survive" (NRC 2002). For that reason, the committee believes that social-science and economic issues related to the six challenges are also appropriate subjects of research for the NEON observatories to support. Although NEON's major emphasis will be research on the nature and pace of biological change, the causes and consequences of this change are tightly linked to human systems, and this linkage should not be ignored in the overall NEON research portfolio.

The nation faces another great challenge: the necessity to communicate scientific understanding of the environment to its citizens and policy-makers. NSF, in its NEON proposal, has recognized that scientists represent only a portion of the user community for NEON, and it envisions students and teachers from kindergarten through postgraduate levels will use NEON information for educational activities and NEON facilities for research. The American public will also use NEON to get up-to-date information about environmental issues. The committee therefore supports a major educational and outreach role for NEON.

The six environmental challenges and the educational challenge have several common features that dictate that they be addressed through a nationwide network of sites. They are all regional, continental, or global in extent; for instance, invasive species and emerging diseases are of concern precisely because they spread across large portions of the nation and have substantial effects on human health, agriculture, natural resources, recreation, forestry, and other economically important endeavors. Second, the problems are multicausal and embedded in biologically and physically complex, large-scale systems; for instance, climate variability and change modify the structure and functioning of ecosystems, and changes in ecosystem structure, such as conversion from forest to pasture, can affect climate by changing the evapotranspiration rate of water. Third, addressing the biological aspects of the environmental challenges requires information on abundances and dynamics of many interdependent species. In the past, collection of such information was a painstaking process that could be accomplished only by highly trained scientists. Finally, to successfully address the environmental challenges would require comparative analysis of ecosystems conducted in the context of long-term, time series observations of key ecological processes and properties; and multiscale research on and monitoring of the propagation of variability across local, regional, and continental scales. The evolution of instrumentation—from molecular probes to high-resolution satellite images and sophisticated software for their analysis—now allows characterization and documentation of biological changes in a more structured manner and over a broad range of time and spatial scales than was previously possible. Technological advances now facilitate the development of national biological networks for large-scale research, such as that described in the NEON proposal.

Well-controlled multifactor experiments that are replicated across a region or the nation and detailed broad-scale observational studies are essential if we are to address the grand environmental challenges faced by the nation. Experiments can control for the confounding effects of variables and thus promote a clear understanding of cause-effect relations. Experimentation should be complemented by long-term observations and some large-scale long-term monitoring that would demonstrate trends and provide signals for environmental changes. Just as a nuclear accelerator allows physicists to address fundamental questions that could never be answered observationally, a "climate accelerator" might allow environmental scientists to determine some of the potential changes in ecosystems in response to climate change without having to wait for 50 or 100 years of observation. *Climate accelerator* is a term that the committee uses to describe a large chamber with controlled environmental conditions. Environmental condition in the chamber can be manipulated to imitate and accelerate climate change—hence its name. Such manipulations might provide insights on an ecosystem's resilience to rapid climate change. Similarly, a "nitrogen-deposition accelerator" would allow researchers to accelerate nitrogen deposition in controlled conditions. A series of nitrogen-deposition accelerators could be constructed in an array of terrestrial, freshwater, estuarine, and marine habitats to determine the multiple effects of anthropogenic increases in nitrogen deposition from the atmosphere or from groundwater or rivers. A climate accelerator or a nitrogen-deposition accelerator would require major investments in facilities and infrastructure.

This chapter outlines briefly the nature of the six ecological and environmental challenges and how a national network of biological infrastructure like NEON would contribute to addressing them. The six challenges are presented in alphabetical order, and the committee feels that addressing any of them would advance environmental science. The contribution of a network of biological infrastructure to education and how they complement each other are also discussed.

BIODIVERSITY, SPECIES COMPOSITION, AND ECOSYSTEM FUNCTIONING

Biodiversity (or biological diversity) refers to the number of species and the extent of genetic variability in those species in a given site. *Species composition* refers to the array of species and their relative abundance in a community in a given site. Human actions are having major effects on both biological diversity and the species composition of ecosystems (NRC 1997). For example, modern forestry practices often involve replacing the diverse trees that had inhabited a recently harvested site with one strain of one species. That has been done repeatedly in the Pacific Northwest, where Douglas fir was planted, and in the Southeast where loblolly pine are planted after forest harvest. Similarly, intensive grazing often leads to the local loss of grassland plant species, as does the deliberate planting of various pasture species. Atmospheric deposition of nitrogen that originated in agricultural fertilizer or high-temperature combustion of fossil fuels also leads to reduced plant diversity and to shifts in plant community composition. Fire suppression, habitat fragmentation and destruction, overexploitation of natural resources, species extinctions, and many other human actions also cause large changes in ecosystem biodiversity and composition.

Research has shown that such changes in diversity and composition may affect the stability, productivity, carbon storage, invasibility, and disease incidence of ecosystems and the nature and value of services that they provide to society (e.g., Naeem et al. 1996, Tilman et al. 1996, 2001, Hector et al. 1999, Loreau et al. 2001). The longest-term biodiversity study is an experiment begun in 1994 at Cedar Creek Long Term Ecological Research (LTER) site in Minnesota and still running. That endeavor has determined the effects of manipulated plant biodiversity and composition on ecosystem productivity, nutrient dynamics, and disease dynamics (Tilman et al. 2001). It has been shown that the loss of plant diversity in those prairie grasslands led to decreased productivity (Figure 2-1), decreased retention of the limiting resource, decreased

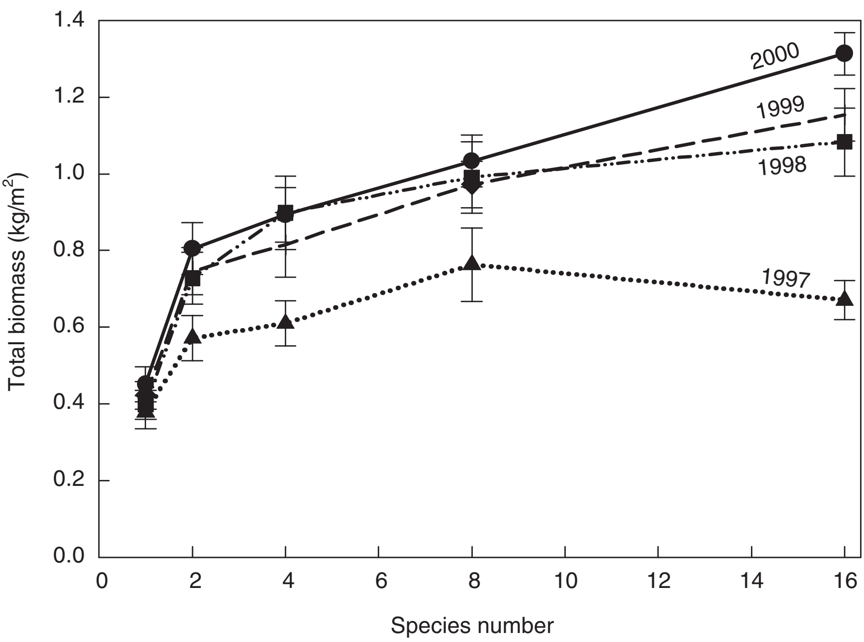

FIGURE 2-1 Relationship between total biomass and species diversity of an experimental prairie-grassland in Cedar Creek, Minnesota. Plant biodiversity (number of species) and plant composition were controlled in this experiment. SOURCE: Tilman et al. 2001.

removal and storage of atmospheric carbon dioxide, increased incidence of species-specific fungal diseases of leaves, and decreased insect diversity (Tilman et al. 1996, 2001, Mitchell et al. 2002, Haddad et al. 2001). A similar experiment was performed in European grasslands and was replicated in eight nations of the European Union, from Ireland and Sweden to Portugal and Greece (Hector et al. 1999).

Those two field experiments have generated numerous questions and controversies in ecology because it is not known whether the experimental results observed would apply to other grasslands, let alone to other terrestrial, lake, or coastal ecosystems. That raises a central issue: How well can results from one or two studies be generalized and applied to other localities and other ecosystem types? How can results be scaled up from one site to a continent? For example, in the Minnesota study, ecosystems planted to 16 prairie grassland plant species removed and stored 2.7 times as much carbon dioxide as did ecosystem planted to a single species. Does that imply that managed forests that are planted to many tree species would remove and store more carbon? Might the number of fish species in a fishery influence its productivity and stability? Might the biodiversity of any type of ecosystem influence the flow and quality of goods and ecosystem services that it provides to society? Answers to such fundamental questions require a continental-scale, coordinated research program.

The same experiments that showed that biodiversity affected various ecosystem processes also showed that the species composition of ecosystems was as important as biodiversity. Management practices—including grazing timing and intensity, the identity of grazing species, fire frequency, logging frequency and methods, reforestation or revegetation methods, and nutrient loading rates—all affect both the biodiversity and the species compositions of terrestrial and aquatic ecosystems. Biodiversity and species composition, in turn, determine the flow, quality, and economic value of the goods and services that the ecosystems produce.

To seek solutions to declines in ecosystem services due to diseases, species invasion, altered biogeochemical cycles, climate change, and land use, we need to know how these phenomena affect species composition and biodiversity. Few sites across the nation have regular inventories of species abundances, and most such inventories are limited to a few types of species (such as tree species or bird species); this leaves the vast majority of their biodiversity unidentified and not quantified. Such data should be collected in a variety of sites that span the major natural and managed terrestrial, freshwater, and coastal ecosystem types of the nation. Biodiversity surveys should be closely tied to experimental studies of the effects of biodiversity and species composition on ecosystem function and provision of services.

ECOLOGICAL ASPECTS OF BIOGEOCHEMICAL CYCLES

Alteration of biogeochemical cycles on regional, to continental, and global scales is a hallmark of human activity. We fix nitrogen from the atmosphere for agriculture or as a byproduct of combustion. We return carbon stored in fossil fuels to the atmosphere. We mine, smelt, transport, use and discard rare elements in support of an industrialized society. We create and release large quantities of pesticides, herbicides, fungicides and other persistent organic pollutants. Products and byproducts of our various actions escape to the atmosphere and hydrosphere and are transported over long distances, establishing connections between centers of human activity and "remote" regions.

Humans are inadvertently conducting a global experiment by modifying biogeochemical cycles through mining, combustion of fossil fuels, large-scale conversion and use of global landscapes, and modification and use of such critical elements as agricultural fertilizers. Many anthropogenic toxicants, such as mercury and polychlorinated biphenyls, are transported from their sources to distant and dispersed areas through the atmosphere. The basic elements of life and important toxins are being distributed at regional and continental scales, and may be deposited as 'toxic snow' in remote and seemingly pristine sites as alpine and northern lakes (Schindler 1999). Emissions of carbon, nitrogen, and sulfur have altered their availability to land and water biota and created shifts in biodiversity and ecosystem function. Heavy metals and organic compounds are transmitted to soils and waterways and are often accumulated and concentrated through food chains.

Common characteristics of such alterations from preindustrial conditions include an increase in cycling rate through the atmosphere and biosphere, increases in the atmospheric reservoir, and enhanced bioavailability. For example, it is estimated that humans have more than doubled the rate at which reactive forms of nitrogen are created from the relatively inert N_2 in the atmosphere. The production of nitrogen fertilizers with the Haber-Bosch process, high-temperature combustion of fossil fuels, and an increase in the cultivation of legumes are the primary causes of the doubling of terrestrial nitrogen inputs. Similarly, human activity now dominates global phosphorus and carbon cycling, land use, marine fisheries, and much of the hydrologic cycle (Vitousek et al. 1997, Carpenter et al. 1999, Postel 1999).

Although increased cycling of carbon, nitrogen, sulfur, and phosphorus increases primary productivity, it also causes loss of biodiversity, changes in dominant species in ecosystems; production of byproducts, such as aluminum, other heavy metals, and tropospheric ozone, and other harmful conditions. For example, algal biomass decomposition that results from increased primary production in aquatic systems can overwhelm oxygen supplies, leading to eutrophic and anoxic conditions.

All those adverse effects are caused by the transport of locally produced compounds, wastes, and byproducts through the regional atmosphere and waterways to adjacent or distant areas of deposition and response. Therefore, understanding biogeochemistry on regional, continental, and global scales is at the heart of addressing the social and environmental problems resulting from changes in the distribution and concentration of elements. For example, carbon dynamics and sequestration in landscapes are the subjects of one of the most socially relevant biogeochemical studies that need to be addressed on a continental scale. Current estimates of carbon storage in the ecosystems of North America depend on the method used to derive.

The development of the eddy covariance method for measuring net carbon balances over short periods has revolutionized ecosystem biogeochemical studies. Eddy covariance provides a new window into ecosystem function that increases our understanding of the processes and controls that determine element balances. Over the last decade, tremendous advances have been made in the reliability and standardization of the basic measurement system and in the understanding of the physical and mathematical constraints on the interpretation of the signal received. Those developments make the technology well poised for much wider application. Currently, the United States sponsors, through the activity of a number of different agencies, a network of eddy covariance towers designed to measure net carbon balances over different ecosystems. The current system lacks both adequate replication and spatial coherence because of the mixed sources of funding and the lack of a national vision.

The congruence of national need, developing technology, and a nascent scientific network means that large gains in our measurement and understanding of carbon fluxes over native and modified ecosystems can be realized immediately through a national network of net carbon balance observatories. Such a network would benefit from the ability to plan, a priori, the optimal number, placement, and operation of a large number of replicate measurement systems. The existing AmeriFlux network (see Plate 1) provides the best current basis for making such estimates, but the network is inadequate with respect to spatial coverage, stratification by vegetation type and land use and management practices, and consistency of the sensors. For example, existing eddy covariance systems tend to be in secondary forests or other relatively stable systems that are undergoing relatively rapid carbon accumulation. Placements are beginning to expand into experimentally-modified or more recently disturbed areas, but such systems are still underrepresented.

A set of eddy covariance towers could be deployed to compare directly the effects of different land-use patterns, water-availability regimes, or pollution-deposition rates on gross and net carbon exchange. Continuous collection of flux data from such sites provides the basic information needed to test fundamental physiological hypotheses on land-use, water, and pollutant effects and would lead to the development of better models.

ECOLOGICAL IMPLICATIONS OF CLIMATE CHANGE

The most recent Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2001a) confirmed a substantial warming trend in the 20th century and strengthened the causal link between increasing greenhouse gases and global warming. Global temperatures rose by about 0.6°C in the last century and are expected to rise further by 1.4-5.8°C in this century (IPCC 2001a). During the 20th century, the United States warmed by 0.8°C (1.4°F). Rates of sea-level rise are expected to increase with climate change. Observed changes in natural systems over the past century clearly indicate a biological response to global climate change occurring worldwide (IPCC 2001b). Climate change has affected about half the wild species studied on global and national scales (Parmesan and Yohe 2003). Yet, within the United States, ecological monitoring has been inadequate to assess the effects of recent climate change on a national scale. Furthermore, small-scale local experiments typical of previous funding are insufficient to provide a mechanistic understanding of observed biological responses for more than a few select species or target communities. Development of detailed biological-effect scenarios for a wide array of wild species and major ecosystems will require coupling of long-term monitoring with experimental manipulations in a replicated design across the major ecosystems of the nation.

Characterization of climate change is possible only on regional to global scales, because data from single locations are extremely variable. Similarly, assessment of biological responses to climate change requires synthesis of data from many locations. Although the climatalogical data archived by the National Climatic Data Center provide a reasonable basis for assessing changes in the physical climate of the United States, the biological impact of climate change is not being addressed adequately on a national scale. Current assessment of the two major biological effects of climate change—changes in timing of biological events and species' distributions—comes primarily from nonrigorous amateur wildlife recording added to a handful of incidental scientific studies that have provided local, long-term censuses on a few species. Experimental studies of climate-change effects represent only a few of the ecosystems in the United States, are not standardized (for example, one might use overhead infrared lamps and another heated cable in the soil), and are generally not designed to look for complex responses (for example, including both animals and plants and their interactions). Finally, existing assessments of carbon flow between atmosphere and ecosystems (via eddy flux towers) are inadequate to characterize total carbon balance in the United States and provide little information on carbon balance in different ecosystems and on different land use and management practices (Houghton et al. 1999; see section on biogeochemical cycles).

An equally important component of climate-change effects is the critical role of physical and biological feedback on climate (Hansen et al. 1984). Changes in land cover (vegetation types and snow cover) affect albedo (reflection) of solar radiation and the proportion of radiation that goes into latent heat (equivalent to evapotranspiration) relative to sensible heating of the land surface; thus, the changes alter local climate. Sharp gradients in areas of vegetated and nonvegetated surfaces (characterized by the Bowen ratio, or ratio of sensible to latent heat) are known to cause "land breezes" and hence affect climate especially during the warm season (Avissar and Pielke 1989). Changes in vegetation affect soil moisture, nutrients, and humidity. On larger scales, the interaction of soil-moisture stress and evapotranspiration has been shown to control the variability of climate over the interior of the Northern Hemisphere land areas in summer (Koster and Suarez 1995). Furthermore, modeling studies have shown that major changes in land cover, such as Amazonian deforestation, can have global effects on climate. Studies of biological feedbacks on climate require replicated manipulations of species' abundances and community structure which will be possible only with substantial scaling up from current designs.

ECOLOGY AND EVOLUTION OF INFECTIOUS DISEASES

Few, if any, scientists could have predicted the scale on which and the extent to which infectious-disease agents have increased in global prevalence and severity over the last 25 years. Emerging infectious diseases are those whose incidences have increased within the last 2 decades or threaten to increase in the near future. The categorization as an emerging infectious disease may be due to the recognition of the spread of a new agent, to the recognition of an infection that has been present in the population but has gone undetected, or to the recognition that an established disease has an infectious origin.

Diseases have been emerging at an increasing rate in wildlife and plants for the past few decades with devastating consequences for biodiversity conservation and human population welfare (Daszak et al. 2000; Anderson and Morales 1994). For example, chronic wasting disease in deer herds is estimated to have cost Wisconsin $10 million and Colorado $19 million in 2002 alone (<http://www.aae.wisc.edu/www/pub/sps/stpap450.pdf>) because of reduction of spending by non-resident deer hunters. Diseases of trees in forest, diseases of animals that are valued by tourists, and diseases of plants that change the aesthetic value of ecosystems represent an enormous cost to the nation's primary productivity and tourism.

Wildlife also act as a reservoir and can be an important source of transmission of infectious diseases to humans (IOM 2002). Indeed, 61% of all human pathogens are capable of natural transmission between animals and humans (WHO 1959) and are thus classified as zoonotic (Taylor et al. 2001). Because most zoonotic infections in humans are usually acquired from the environment and most emerging disease outbreaks are related to ecological disruptions, the study of zoonotic epidemiology requires fundamental ecological knowledge. Although vaccination for and control of infections in humans are important, the ecological and evolutionary selection pressures that cause diseases to emerge or develop resistance to treatment should be identified so that disease emergence and spread can be prevented.

Our first challenge is to identify ecological conditions that lead to disease emergence. For example, the 1993 outbreak of Hanta virus pulmonary syndrome (HPS) caused by the Sin Nombre Hanta virus in the US Southwest was probably caused by a cascade of ecological events that led to increased exposure to the virus (Figure 2-2). In particular, dry years followed by wet summer increased ecosystem productivity, thereby increasing food for rodents. Rodent predators had been reduced by hunting, so rodent abundance rose virtually unchecked, and this led to increased transmission of the virus in the deer mouse population and ultimately to humans.

In addition to identifying ecological factors that promote disease emergence, we also need to understand the factors that promote disease spread and microevolution dynamics. For example, the virus complex that causes tick borne encephalitis (TBE) most likely originated in the Far East and spread from Japan (as Omsk virus) to the states of the former Soviet Union. From the Soviet Union, it spread to other European countries, including Slovakia, Austria (as western TBE), Spain (as Spanish encephalitis), Scotland, and Norway (Gould et al. 2001). Shifts in virus strains have been hypothesized to be caused by human-induced changes in host community and vector ecology. Research has indicated that rapid late-summer cooling tends to synchronize the immature stages of the ticks, leading to tick-to-tick transmission of TBE on the host (Randolph et al. 2000, Rogers et al. 2001). At the same time, large communities of mammalian hosts (such as a large flock of sheep) would promote disease transmission. Subtle seasonal changes in climate coupled with land-use changes that increase host availability can trigger disease outbreaks.

Comprehension of the spread of TBE on the continental scale would provide us with insights about the ecological conditions that stimulate emergence and spatial flow of similar diseases. For instance, West Nile virus, which has spread across the United States in the last few years (Plate 2), is a close relative of TBE (Gould et al. 2001). Detailed knowledge of climatic conditions that influence the mosquito life cycle and the availability and susceptibility of hosts is necessary for the prediction of the spread of West Nile virus. Within host and transmission dynamics should be linked to provide an understanding of how the disease spreads spatiotemporally. Such information can then be projected from the landscape to continental scale. Integration of ecological understanding

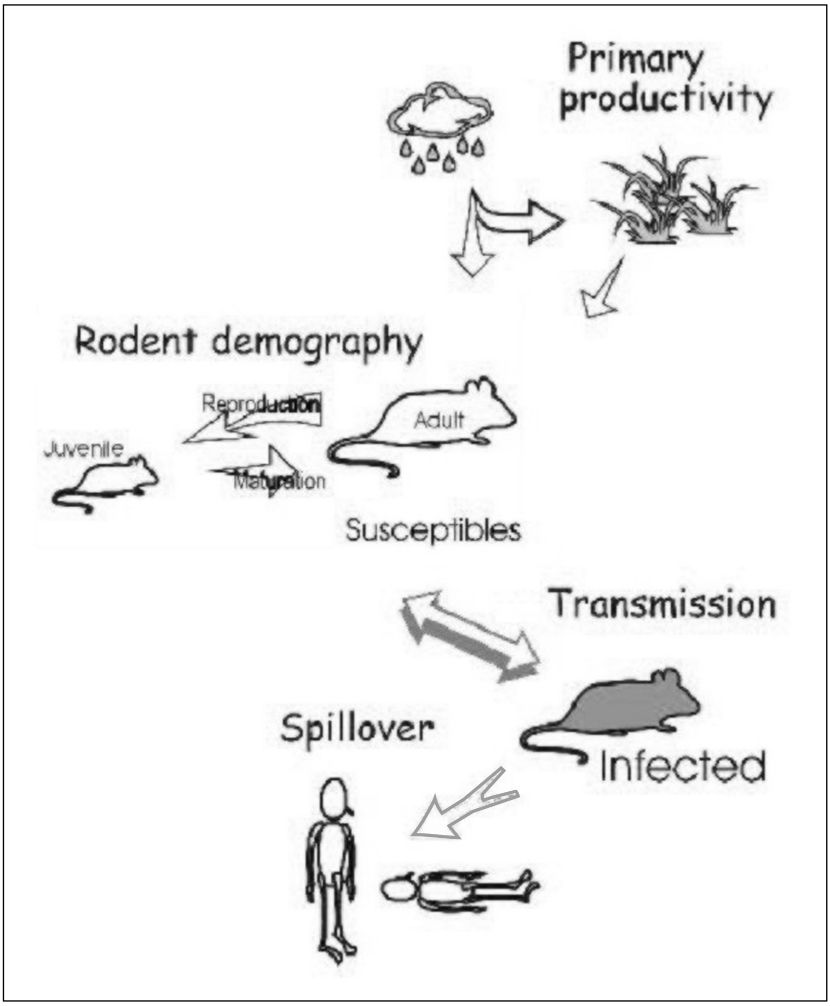

FIGURE 2-2 A schematic overview of the cascade of ecological events that leads to increased human risk to Hanta Pulmonary Syndrome. The central ecological "engine" is the production of susceptible hosts ("Rodent demography") through rodent reproduction. Susceptible hosts acquire infection from infected individuals through contact transmission ("Transmission"). A cascade of increased risk is initiated when environmental conditions (notably primary production) favor rodent reproduction and recruitment (Primary productivity) and ends with human-rodent association leading to cross-species infection (Spillover).

with epidemiology and microevolution dynamics would permit prediction of infection probabilities on a continental scale.

A network for monitoring the spread of emerging diseases and for studying the ecological factors that promote disease outbreak and the evolution of diseases would help in identifying disease hot spots, where the next emerging disease would appear, and how it would influence human, wildlife, and plant communities. A deep understanding of the ecology of wildlife, plant, and zoonotic diseases can help us to devise precautionary measures for and adaptive responses to disease emergence.

INVASIVE SPECIES

Human commerce and transport fuel economic development but also inadvertently serve as a conduit for the transfer of non-native species into new ecosystems. Once released into new environments, foreign species can become ecological dominants, disrupting agriculture, ecosystem function, or water flow, and displacing native species.

Invasive species occur in every ecosystem in the United States, from shallow bays and rivers to lakes, forests, farms, and grasslands. The freshwater zebra mussel was brought to North America in the ballast water of commercial tankers, and was first discovered in 1988. Zebra mussels have now spread to many states in the United States (Plate 3) and causes expensive damage each year by clogging freshwater pipes. Most agricultural weeds are introduced species. Indeed, most invasive plant species were deliberately introduced into new habitats via the horticultural trade. Although only a small percentage of plant species introduced as ornamentals become invasive, thousands of novel plant species are allowed to be imported into the United States every year because there are no known ways to identify beforehand the ones that will cause the next major invasion. The introduced gypsy moth destroys coniferous forests when it escapes insecticide control and spread from the suburbs of Boston to the coniferous forests of Oregon in the last century. San Francisco Bay has over 100 invading marine species, including the Atlantic shipworm, which is capable of eating wooden docks and destroying seawalls. Overall damage to the economy by invasive species has been estimated to be $137 billion per year (Pimentel et al. 2000). Because no ecosystem in the United States is immune to the damage caused by invaders, and because invaders often jump from one ecosystem to another, any response must involve a national-level effort to track and control invaders.

The most rapid invaders tend to be fast-growing species that have escaped their natural controls. Recent data suggest that invasion rates increase when native parasites do not target invading species (Torchin et al. 2003) or when local biodiversity is artificially lowered (Stachowicz et al. 1999). However, there are no general principles for differential susceptibility of ecosystems to invasion, and management to reduce invasion currently consists solely of reducing foreign species introductions. As global trade increases, invasions are likely to multiply. The global village of future human commerce will contribute to the creation of a global ecosystem biased toward weedy species unless invasion can be understood as an ecological process sufficiently to allow forecasting of the invasiveness of species and prediction of which potential biological agents would both be effective in controlling an exotic species and have the fewest detrimental effects on natural and managed ecosystems.

Observations of invading species tend to be idiosyncratic, and data on the rate of spread of species through different ecological communities are sparse. For example, green crabs invaded the coast of Maine in the 1930s from a 19th century introduction in New Jersey but there have been few observations of the pace of invasion. Similarly, few experiments on the susceptibility of different ecosystems to invasion have been conducted, and none have examined how a single species invades multiple habitats.

The national problem of species invasions cannot be addressed without a national system for tracking invasions and a set of research facilities dedicated to understanding why some ecosystems are more than others prone to invasions and why some species are more likely than others to become invasive. Studies of where invading species enter the United States, their routes of spread and points of control, the speed at which they move through different ecosystems, and the concomitant changes in native species all require monitoring systems that are coordinated across different ecosystems on a continental scale. Such monitoring efforts combined with experimentation would generate models that assess ecosystems' vulnerability to species invasion.

LAND USE AND HABITAT ALTERATION

In the National Research Council report *Grand Challenges in Environmental Sciences* (NRC 2001), the challenge related to land and habitat use was described aptly:

> Humans have dramatically altered the Earth's surface. These changes in land cover—the land surface and immediate subsurface, including biota, topography, surface water and groundwater, and human structures—are so large and rapid that they constitute an abrupt shift in the human-environment condition, surpassing the impacts of all past epoch-level events (e.g., the domestication of biota, the industrial revolution) since the rise of the human species. Indeed, they approach in magnitude the land-cover transformations that have occurred at transitions from glacial to interglacial climate.

Whether anthropogenic in origin or the result of natural events, such as wildfire, changes in land and habitat use can affect a full suite of environmental characteristics both locally and nationally. Land-use practices in one region can affect people and ecosystems 1,000 miles or more away. For example, intensive agriculture in the upper Midwest affects water quality in the lower Mississippi and fisheries in the Gulf of Mexico (Downing et al. 1999). The damming of rivers—a major form of habitat use—can provide water for agricultural and urban use and can provide hydroelectric power. However, damming can also affect fisheries and threaten species with extinction. Because materials and organisms are transported from one site to another through the atmosphere, groundwater, streams, and rivers, land-use and habitat alteration in one region can have substantial effects on other regions. Thus, land-use and habitat alteration have to be examined and understood on regional to continental scales.

In the United States, agriculture and forestry greatly influences land-use practices. After the settlement of the United States in the 16th to 19th centuries, massive changes in land and aquatic habitats occurred in North America. The forests of the East were cut to produce pastures and plowable fields. The prairies of the central states became the granaries of the nation. The forests of the Northwest were clearcut to provide timber for the nation. The rivers of the West were dammed so that the dry lands of the region could be used to cultivate produce.

Those land and habitat use and management practices have provided many of the initially desired benefits, but also have had a range of unintended impairment to ecosystems. For instance, the NRC report on *Grand Challenges in Environmental Sciences* (NRC 2001) states that

> Human use of land, that is, what people do to exploit the land cover, has been the primary culprit in the estimated 2.95 million km^2 of soils whose biotic function has been significantly disrupted by chemical and physical degradation—including 1.13 million km^2 disrupted by deforestation and 0.75 million km^2 by grazing. In addition, agriculture currently consumes 70 percent of total freshwater used by humankind, much of which is accounted for by the rapid expansion of irrigation, which annually withdraws some 2000-2500 km^3 of water.

Land and habitat use can increase disease spread, harm species or even threaten them with extinction, decrease the flow of essential and valuable ecosystem services, and affect the production of food, fiber, and fuel (NRC 2001). We concur with the National Research Council report, which concluded that

> land-use and land-cover dynamics and their spatial patterns play a significant role not only as drivers of environmental change, but also as factors increasing the vulnerability of places and people to environmental perturbations of all kinds. Improved information on and understanding of land-use and land-cover

dynamics are therefore essential for society to respond effectively to environmental changes and to manage human impacts on environmental systems.

A nationwide network of facilities would allow comparative environmental studies—biodiversity, biogeochemistry and water quality—of ecosystems subject to different land use practices.

SIX LARGE-SCALE ENVIRONMENTAL CHALLENGES

On the basis of observations, facts, and analyses (set forth in detail earlier in this chapter), the committee identified six critical environmental challenges that are of national concern and that can be addressed only by research performed in a coordinated manner on regional to continental scales—research that would require a network like the National Ecological Observatory Network (NEON). Only a nationwide network of sites that have a common infrastructure for experiment and observation can adequately address each of those challenges. Plates 4-7 illustrate examples of large-scale infrastructure and experiments that contribute to the advancement of ecology and environmental science. Just as nuclear accelerators have proved to be essential for advancing our knowledge of subatomic physics, networks of infrastructure that facilitate and accommodate well-replicated ecological experiments are essential for advancing our knowledge in ecology and environmental science.

ENVIRONMENTAL EDUCATION AND OUTREACH AS NATIONAL NEEDS

The National Science Board, in its recent report *Environmental Science and Engineering for the 21st Century: The Role of the National Science Foundation*, stresses that the National Science Foundation is being looked to for leadership in environmental research, education, and scientific assessment by citizens, other federal agencies, professional societies, scientists, and government officials, and notes that "Scientific understanding of the environment, together with an informed, scientifically literate citizenry, is requisite to improved quality of life for generations to come" (NSB 2000). Fulfilling that role and the educational expectations is a challenge that NSF could meet with careful planning.

Scientific progress in the six themes described above requires an interdisciplinary approach. Although multidisciplinary research is collaboration among scientists in different fields, interdisciplinary research requires the integration of multidisciplinary knowledge. Yet few environmental scientists have the broad training required to conduct interdisciplinary research (NRC 2001).

Undergraduate education faces similar challenges because how scientists design, perform, and analyze experiments and how they collaborate, and exchange information are undergoing rapid and dramatic transformations. Links between the physical and biological sciences, technology, and mathematical disciplines are becoming essential. In contrast, undergraduate biology education has changed relatively little during the last 2 decades. Training and education of future biologists are geared mostly toward the biology of the past, rather than to the biology of the present or future (NRC 2003a). As is true of research, undergraduate science education needs an interdisciplinary transformation to meet the needs of 21st century biology.

The role of science in K-12 education requires national attention. The nation has established scientific literacy as a central goal for K-12 education, but to date this goal "eludes us in the United States" (AAAS 1989). Scores of national and state studies have concluded that—as judged by international norms, national standards, and state requirements—the US K-12 education system is failing to educate many of its students. The reform of education in science, mathematics, and technology should be one of America's highest priorities (AAAS 1989).

Students who do not understand the natural world, do not have the knowledge and skills needed to make informed decisions, or do not understand the workings of the ecosystem in which they live cannot function as responsible stewards. Education to understand the relationship between humans and the rest of the biosphere should draw from multiple scientific disciplines—social science, geology, geography, meteorology, chemistry, physics, ecology, and economics. Yet few curricula and textual material include such an integrated approach, and K-12 teachers have usually received little training in environmental science and are rarely equipped with the knowledge and skills needed to work beyond textbooks (PCAST 1998).

In part as a result of deficiencies in science education, "Americans are ill prepared to understand the complex and intractable environmental issues that will be our greatest challenges in the years ahead," according to the 1999 *National Report Card on Environmental Readiness for the 21st Century* (NEETF 1999). The majority of the public harbor serious misconceptions on such issues as global warming, air pollution, and water quality. A 1998 survey of adult Americans by Roper Starch Worldwide reported that when specifically tested on environmental knowledge, most Americans had misinformation and expressed "beliefs" that were myths. Americans averaged just 2.2 correct responses out of 10; even random guesses would have produced 2.5 correct answers (NEETF 1998). Moreover, the survey reported a strong correlation between environmental knowledge and behavior. Activities or behavior that benefit the environment increase proportionally with environmental knowledge.

Despite their lack of knowledge, most Americans remain supportive of environmental protection and the desire to make the environment and economy a win-win issue, are engaged in environmental activities and courses, and 95% American adults support the teaching of environmental education in our schools (NEETF 1997). An increase in public understanding of and involvement in ecology and environmental science would make Americans more informed citizens and more likely to support environmental policy that best balances the multiple tradeoffs that society faces.

CHAPTER THREE

Concept and Implementation of the National Ecological Observatory Network

After identifying the major environmental challenges facing the nation, the committee proposed that the first NEON observatory should focus on one challenge and that the network should grow by addressing additional challenges. Each theme-based NEON observatory would comprise sites that span the continent and infrastructure for integrated suites of experimental manipulations, monitoring, and synthesis directed at its theme.

One of the four tasks in the charge to the committee was to address the question, Will NEON, as conceptualized in the series of five community workshops, be able to provide infrastructure and logistical support to address ecological and environmental questions of national concern? Our answers to the question are provided in this and later chapters. The answers are not simple; such an evaluation must be based on a comparison of sometimes divergent concepts proposed in the various workshops. In pursuing this task, the committee unavoidably came upon aspects of the National Ecological Observatory Network that it felt could be implemented in better ways. We communicate these findings as an essential part of our answer to the stated question.

PROPOSED CONCEPT AND IMPLEMENTATION OF NEON

The NEON program as currently envisioned by the National Science Foundation (NSF) would be driven mainly by the science community—an investigator-driven approach that has been highly successful in generating creative research by the scientists funded by NSF. That is, requests for proposals would be issued with only the broadly specified goals of NEON and the requirements of and constraints on regional NEON observatories. The designs set forth in the winning proposals would dictate what each regional NEON observatory ultimately became. Thus NEON observatories would take shape only after infrastructure funding under the Major Research Equipment and Facilities Construction (MREFC) account has been secured from Congress.

To be successful, NEON would have to attract a large number of the brightest and most productive environmental scientists in the nation, who must be willing to dedicate their careers to their NEON research. The investigator-driven approach proposed by NSF has advantages and disadvantages. In the committee's opinion, the peer-review process used to select the most promising investigator-proposed research from a suite of numerous competing proposals is the most important factor that has allowed NSF to be so effective. In addition, because investigators articulate their insights and propose the novel scientific approaches that they find most promising, funded NSF investigators are extremely dedicated to their research. Thus, the committee agrees with NSF that investigator-driven research must be a central feature of the formulation and implementation of NEON.

However, the currently envisioned approach requires that NSF request new MREFC funds from Congress without being able to show Congress how the funds would be used or what each NEON observatory would look like or do. That is inconsistent with the normal congressional approach to MREFC funding decisions; Congress expects detailed scientific justification of goals and plans and detailed descriptions of proposed MREFC facilities, including blueprints and cost estimates. The deviation from MREFC funding requirements could decrease the chance that NEON would be established with MREFC funds. In addition, the current approach would build a NEON network piecemeal via funding of one or two regional observatories at a time. Thus, NEON will not be a truly integrated national network of sites until all the observatories are funded and built which could take more than a decade. If, as currently proposed, different universities and consortia submit proposals and obtain funding for design and implementation of each NEON regional observatory, it would be difficult to ensure an integrated and coordinated approach to each of the major environmental challenges and proper replication and coordination of critical experiments and observations at a suite of appropriate sites across the nation. But the drawback of an issue-driven approach is that NSF may be over prescriptive in the NEON design, which could potentially reduce the creativity and commitment of investigators, cause less efficient resource use, and have NEON fail to attract the most appropriate scientists.

For NEON to be efficient in addressing the nation's major environmental challenges, the committee believes that a middle ground needs to be found between the issue-driven and the investigator-driven approaches. The ideas and creativity of a large number of highly productive scientists should be incorporated into NEON design to ensure the scientists' dedication to NEON projects. A sufficiently detailed vision of NEON needs to be presented not only to fulfill MREFC funding criteria but also to ensure that research programs at NEON observatories would provide information from experimentation and observations that could aid local, regional, and national policy-makers, park and wildlife-preserve managers, Forest Service personnel, overseers of agricultural sectors, land-use planners, conservation biologists, water managers, and others in environmental decision-making. Hence, NEON research teams should be multidisciplinary and include social scientists, such as economists and political scientists, in addition to ecologists and environmental biologists.

Given NSF's current implementation plan for NEON, it is difficult to identify the infrastructure needed without knowing the type of research to be conducted in the full suite of regional observatories. For example, a regional observatory might procure infrastructure of little use to itself in the false belief that it would be useful to as-yet-unnamed observatories at some future date. The committee is also concerned that the nationwide aspect of NEON would not be realized if the regional observatories are built two at a time. Hence, we suggest that one way to achieve the objectives would be for NSF to focus NEON explicitly on such environmental challenges as presented in Chapter 2. The six environmental challenges have already been suggested as issues that could be addressed in NEON observatories by NSF and AIBS (NSF 2002d, AIBS 2003), and three of them have been recommended as priority research areas that deserve immediate investments (NRC 2001).

An advantage of having NEON focus explicitly on major environmental challenges is that NEON could be implemented more efficiently and effectively. Each NEON observatory would be national in scope and focused on one particular challenge. Sites in an observatory would be selected simultaneously and located strategically across the nation to ensure adequate regional and national coverage for addressing the challenge. The research focus of each theme-based nationwide NEON observatory would guide the selection of sites and help to identify its essential facilities, infrastructure, and research support. Each later NEON observatory would build on existing infrastructure as needed to pursue its particular challenge and the interactive effects of its challenge with those already being studied in established observatories. Six nationwide, theme-based NEON observatories would thus cover all the major challenges that the committee identified.

We envision each observatory as a network of sites spanning the nation with infrastructure, providing the resources for the experimental and observational research needed for its specific theme and for an array of appropriate core monitoring tasks. Experimental sites would be replicated in different habitats across the continent to allow comparative ecosystem analyses. A synthesis center would collate and integrate data and make information available to all workers, modelers, and educators. The design of each NEON observatory would be optimized for its environmental challenge by interactions among the coalition of many multi-investigator and interdisciplinary teams and associated sites competitively chosen from across the nation. Sufficient funds must be allocated for the development of each NEON observatory for it to be a truly nationwide network.

To be effective, each NEON observatory must form partnerships with appropriate federal, state, and local agencies and organizations so that it can coordinate and optimize data collection and sharing. A number of agencies already collect long-term systematic environmental data relevant to the six themes we suggested. NEON observatories could include some of this long-term core monitoring that complements the experiments at selected sites and adds to those datasets. In some cases, sites may be colocated with existing long-term monitoring systems by other agencies. Long-term data could show trends that lay the foundation for hypothesis setting, reveal the status of the system relative to what is being measured, and subsequently lead to a better understanding of the effectiveness of environmental regulations or allow prediction. Moreover, all the observatories in the network should be linked with each other via a central coordinating and synthesis center. Research in each observatory and among observatories should be coordinated cooperatively to increase the effectiveness of the entire NEON program. It is impractical, if not impossible, to design meaningful nationwide experimental studies that explore the full range of interactions among all six environmental challenges, but one or more individual sites in a given NEON observatory could simultaneously address several grand challenges and their interactions.

The creation of a NEON observatory would likely be a multistep process. First, open workshops and working groups should be held to solicit ideas and approaches to a particular grand environmental challenge. The workshop would generate suggestions of potential sites, infrastructure needs and partnerships. Second, investigators' input would be synthesized in peer-reviewed preproposals addressing the challenge that were submitted by different teams for work at particular sites. Finally, there would be discussion and coordination among the chosen teams to finalize plans for the entire observatory. Such a multistep process, with participation of numerous scientists in the design of an observatory, would ensure that its equipment, facilities, and core monitoring would meet the research needs of investigators. The finalized plans for the entire observatory would undergo further review and modifications. The goal of such a multistep process is to optimize both the ability of various scientists to contribute creativity and commitment to the observatory and the ability of the multiple teams and sites to pursue their challenge in a coordinated manner. NSF would seek funds from the MREFC and Research and Related Activities (R&RA) accounts for the observatory at the appropriate time during this process.

Matters that need to be addressed in a NEON plan include site selection, equipment acquisition, site management, core monitoring, data management and quality assurance, and specimen banking. NEON sites should be selected for their appropriateness for the research theme of the observatory and likely future observatories. Ideally, most sites would be able to serve several themes, but some sites could be of unique interest to one research theme only. The latter should be kept to a minimum to optimize the efficiency and the integration of NEON observatories. Similarly, instrumentation and equipment at NEON observatories should have the flexibility to incorporate advances in technology and data analyses and to be upgraded in a cost-effective manner.

Managers and providers of basic services would be needed for each observatory and its many sites, and mechanisms should be in place for the selection and directions of the managers. The managers and operators, who would become integral parts of the infrastructure themselves, would be responsible for putting the recommended infrastructure in place and operating and maintaining it. Each observatory must be able to ensure the quality of its massive datasets and to store, archive, retrieve and integrate datasets and make them readily available to all potential users. Those would be the tasks of a synthesis center, or perhaps a virtual synthesis center, which would serve as a focal point for each NEON observatory. The synthesis center would also store data on the systematics of the biodiversity in that network, and could develop tools to improve the efficiency of and capacity for identifying and documenting species.

Environmental-specimen banking is critical because new and better analytical tools will be developed to determine exposure of organisms and the environment to anthropogenic stressors and their effects. Thus, NEON must give careful consideration to central banking of environmental samples in a manner that would preserve their chemical and biological integrity. Such a banking program is already operated by the National Institute of Standards and Technology, which NEON could partner with or emulate. Questions relative to the status and trends of environmental systems that cannot be addressed today may be answered in the future by using the stored samples, archived data, and new analytical tools.

Each theme-specific NEON observatory would have to determine its educational focus and how it would reach targeted audiences, such as K-12 teachers and students, undergraduate and graduate students, and the general public. Environmental-education specialists should therefore be involved in the planning phase of each observatory. We endorse the American Institute of Biological Sciences (AIBS) recommendation that NEON observatories have a public outreach and information office to communicate and disseminate their role, research, and results to the public, and the mass media and to offer on-site tours, programs, and volunteer opportunities (AIBS 2003). To coordinate, facilitate, and assist the observatories in their education function, an education and outreach center should be considered.

The planning, implementation, and operation of each theme-driven NEON observatory could be overseen by a university corporation consortium similar to the University Corporation for Atmospheric Research. Each university, federal agency, or institution that is part of the observatory could become a member. The university consortium would provide administrative structure and a governing council that provides oversight and ensures that the NEON observatory serves the entire scientific community that is addressing its theme.

A permanent coordinating body independent of NSF should be established to oversee the NEON network. The coordinating body would ensure integration and coordination across the network, oversee the network's facility infrastructure, and coordinate establishment of standard procedures for data collection and policies for access to NEON sites, data, and specimens. The NEON program would also need the advice and oversight of an independent body of scientific experts to ensure that the observatories remain focused on their missions and that potential synergies gained by collaborations between and among different observatories are realized. Such a standing scientific coordinating committee could be organized by a consortium of multiple universities.

EXAMPLES OF NEON OBSERVATORIES AND THEIR INTEGRATION

On the basis of the six research themes, the committee outlines here some of the major infrastructure necessary to conduct large-scale research. The brief lists given below are by no means exhaustive or all-inclusive. Rather, they illustrate some of the possible infrastructure and research needs of the NEON observatory that focuses on each theme. More appropriate and complete designs would be generated through open workshops and discussions, the ideas generated in preproposals, and the synthesis of the preproposals chosen for further consideration. Although the construction, implementation, and maintenance costs of NEON observatories could be determined only after comprehensive plans have been drawn for the observatories, they are likely to vary between observatories depending on their focus and plans. Costs may substantially exceed the $20 and $3 million that NSF proposed for the construction and maintenance of each observatory. But the costs of six theme-driven observatories might be comparable to, if not less, than 17 regional observatories proposed by NSF. Program funds, in addition to MREFC and R&RA funds, should be made available for the conduct of research so that NEON facilities could be fully exploited.

Biodiversity and Composition

All the lands of the nation are deliberately or inadvertently managed by their owners. Such management has led to dramatic shifts in the abundances of species in the nation's ecosystems and equally dramatic decreases in biodiversity. The shifts in composition and diversity could strongly influence many processes, including disease dynamics, ecosystem productivity and stability, nutrient dynamics, and water quality. They may also influence human welfare by affecting the services that ecosystems provide to society. To understand better the effects of shifts in biodiversity and ecosystem services, improved monitoring programs must be established to document how various management practices influence composition and biodiversity in the varied terrestrial, aquatic, and marine ecosystems of the nation and how shifts in composition and diversity influence their dynamics, stability, and functioning. The major infrastructure and investments needed to achieve those goals could include

- A network of sites with environmental chambers and field experiments in perhaps 20 ecosystem types representing the diversity of the nation's ecosystems. The sites and chambers could be used to perform experiments designed to determine how and why various aspects of human-driven environmental change affect biodiversity and species composition. Other experiments could focus on the functional ecology of the species to determine how changes in biodiversity and composition affect major aspects of ecosystem stability and functioning.
- Facilities, and equipment for detailed monitoring of species abundances and biodiversity in relation to various perturbations and management practices in sites representing the nation's whole array of terrestrial, freshwater, and marine communities and ecosystem types from across the nation. Although biodiversity and composition monitoring may seem to be a daunting task that requires data collection at 1,000 sites or more, the Environmental Protection Agency, the Forest Service, the US Department of Agriculture, the National Park Service, NSF, and various other national, state, and regional agencies already have programs in place. Detailed monitoring could be achieved once those efforts were coordinated and expanded.
- A national program for archiving type specimens and samples of each species in soils, of water and so on, for future analysis.
- A national data and synthesis center to collate, store, and allow analysis of biodiversity and composition data and related data on site and management practices.

- Sequencing facilities and microscopes for taxonomic and phylogenetic studies.

A biodiversity observatory could collaborate or integrate with existing biodiversity programs to expand the scope and depth of biodiversity research. Examples include

- *BioMERGE.* An NSF-funded research coordinating network dedicated to fostering integration of the study of biodiversity with the study of ecosystem processes (<http://depts.washington.edu/biomerge/about.html>).
- *The National Biological Information Infrastructure (NBII).* A broad, collaborative program to provide increased access to data on the nation's biological resources.
- *Biodiversity and Ecosystem Processes in Terrestrial Herbaceous Ecosystems (BIODEPTH).* A pan-European study of the importance of biodiversity for the functioning of grassland ecosystems. It features the same field-manipulation experiment replicated across a continental network of sites.
- *DIVERSITAS.* An international global environmental-change research program. It is pursuing three core projects: in discovering biodiversity and predicting its changes, in assessing effects of biodiversity change, and in developing the science of the conservation and sustainable users.

Biogeochemistry

Anthropogenic activities have been altering the cycling and distribution of such major elements as carbon, nitrogen, and phosphorus. However, ecosystem structure and function also play an important role in biogeochemical cycling. The primary goal of a biogeochemistry observatory is to provide experimental and observational infrastructure for studying the biotic and biogeochemical responses of ecosystems to spatial and temporal environmental changes. The infrastructure required for large-scale biotic and biogeochemical studies could include

- A nationwide network of experimental nitrogen-deposition accelerators and controlled-environmental soil-warming chambers for studying the effects of major environmental stressors on ecosystems.
- Nested arrays of eddy covariance towers across important environmental and stressor gradients for studying atmosphere-biosphere interactions and net carbon storage with increased spatial intensity.
- Advance remote sensing and geographic information systems to support investigations into previous patterns of land use, to extrapolate site and gradient studies across the region, and to measure spatial and temporal changes in the concentrations and ratios of nutrients in the foliage of forest canopies.
- Instruments designed for monitoring chemical composition in soil and water.
- A mass spectrometer and sequencing center to study the effect of altered biogeochemical cycles on isotopic signatures of nationwide soil and water samples and on the diversity of plants and animals, respectively.
- Nested arrays of eddy covariance towers across important environmental and stressor gradients to study atmosphere-biosphere interactions and net carbon storage with increased spatial intensity and to monitor and assess physiological capacity of plants.
- Automated chambers or CO_2 soil probes for respiration measurements.
- A central facility for standardized equipment calibration.

A biogeochemistry observatory would benefit from partnerships with agencies and programs such as the following:

- *Fluxnet*. A global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of carbon dioxide, water vapor, and energy between terrestrial ecosystem and atmosphere. Over 200 sites are used for continual long-term monitoring.

- *The National Aeronautics and Space Administration*. It has an extensive remote sensing network.
- *National Atmospheric Deposition Program/National Trends Network (NADP/NTN)*. A nationwide network of precipitation monitoring sites. NADP data products include weekly and daily precipitation-chemistry data, annual and seasonal wet-deposition data, and mercury-deposition data.

Climate Change

The central missions of a climate change observatory would be to facilitate research on the effects of different scenarios of climate change on the nation's natural and managed ecosystems and research on how functioning and status of the nation's ecosystems might affect regional and global climate change by influencing greenhouse gases, albedo, evapotranspiration, and so on. To achieve those missions, assessment and experimentation need to be conducted simultaneously and replicated across species' functional groups and ecosystem types. The climate-change observatory might require

- Facilities and equipment for detailed, long-term observations of species dynamics of locally important or interesting species and their relations to climate variability.
- Instruments for the automated collection of detailed physical information, including climate data, dynamics of soil moisture and soil nutrient chemistry, groundwater chemistry, soil and plant respiration, photosynthesis, and release of greenhouse gases.
- Experimental climate accelerators to determine the effects of possible future scenarios of climate change on the composition, dynamics, stability, and productivity of the major ecosystems of the nation. Each accelerator could comprise a set of large experimental units.
- A nationwide network of eddy flux towers to locate and understand the "missing carbon sink" of terrestrial North America and to determine how and why land and habitat use and management practices

in different ecosystems influence carbon storage and release. The eddy flux towers should be at sites in each region that have varied land and habitat uses, and should be calibrated and validated with detailed site data.

- A nationwide network of experimental climate accelerators to determine the effects of likely scenarios of climate change on the composition, dynamics, stability, and productivity of major ecosystems. The climate accelerators could be at a number of different sites, each site having large experimental units.

A climate-change observatory could partner with agencies and integrate with programs and existing monitoring schemes, such as

- *National Oceanographic and Atmospheric Administration (NOAA).* It has the Climate Prediction Center, the Climate Monitoring Diagnostics Laboratory, and the National Climatic Data Center.
- *US Global Change Research Program (USGCRP*). It supports research and observational activities on the interactions of natural and human-induced changes in the global environment and their implications for society.
- *Global Climate Observing System (GCOS).* This was established to ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users.

Infectious Diseases

An observatory for the ecology and evolution of infectious diseases could focus on some of the important and pressing disease issues in plants, wildlife and zoonotic diseases (infectious diseases shared between wildlife and humans). An observatory on infectious diseases could seek to predict the conditions that would increase risk and spread of those diseases, identifying hot spots and the nodes of infection where diseases must pass through for an epidemic to become important. An infectious-disease observatory would aim to facilitate interdisciplinary research to identify the ecological causes of emergence and the changes in evolutionary pressures that can lead to the emergence of virulent strains.

Specific infrastructure needs could include

- Detailed field sites recording seasonal and inert annual variations in disease prevalence and experimental sites coupled with containment facilities. Sites should be distributed in different regions to allow comparisons and replicated within regions.
- Disease-monitoring centers with sequencers, immunology and virology laboratories, and biosecure handling facilities for small-scale experiments (for example, experiments on host dynamics). Sites would require large computational power for running simulation models of the spatial spread of diseases and integrating phylogenetic studies of hosts, parasites, and environmental pressures.
- Vector screening sites related to emergence of disease, such as West Nile virus, with central identification and molecular screening laboratories.
- Epidemiological warehouses for monitoring transmission patterns and routes at the mesoscale where ecosystems level factors could be manipulated. Similar holding systems would be needed to identify selective pressures leading to evolution of new strains.
- PCR-sequencing laboratory for diagnosis of infectious agents.

Potential collaborators of an emerging-disease observatory include

- *The National Wildlife Health Center (NWHC).* A science center of the Biological Resources Discipline of the United States Geological Survey. NWHC is a biomedical laboratory dedicated to assessing the effects of disease on wildlife and to identifying the role of various pathogens in contributing to wildlife losses.
- *Forest Service Forest Health Protection Program.* A program of the US Department of Agriculture Forest Service that conducts annual aerial and ground surveys to monitor the status of destructive insect and disease pests on Forest Service lands.

• *National Institute of Allergy and Infectious Diseases*. This supports basic research on West Nile and related viruses to understand factors associated with the animal or human hosts, the microorganisms, and the environment that influence disease emergence.

• *Centers for Disease Control and Prevention*. This maintains human epidemiological data on vector-borne infectious diseases.

Invasive Species

Research at an observatory for invasive species would have a primary mission of predicting and monitoring the occurrences, spread, and environmental consequences of invasive species. Those species would include microorganisms, insects and other animals, plants, and genetically altered organisms. Achieving the mission would require a mechanistic knowledge of the invasion process and information about species traits and ecosystem states that influence invasions. The observatory's major infrastructure might be expected to include

• Major physical sites, each with containment facilities appropriate for experimental introduction of invasive species into contained communities. Experiments would be designed to determine the mechanisms of interaction among native and invasive species and to enhance our capabilities to assess an ecosystem's vulnerability to species invasion.

• Control hardware and software to monitor environmental alterations and to adjust local conditions.

• A major site serving as a central sequencing center, which could include an existing sequencing center and be equipped with molecular genetic instrumentation and such equipment as sequencers, cloning facilities, chip printers, and microarray readers.

• Facilities at each site to house local synoptic collections. Microscopes, digital photographic tools, microarray readers and gene specific probes would likely be needed.

• Experimental plots at some or all major sites outfitted with equipment needed to alter local environments, such as carbon dioxide addition rings or soil warmers, so as to determine the possible selective advantages that climate change or environmental change may confer on invasive species.

- PCR-sequencing facilities to determine origin and genetic structure of invasive populations.

The invasive species observatory could establish linkages to such agencies and programs as

- *The National Invasive Species Council.* An interdepartmental council that helps to coordinate and ensure complementary, cost-efficient, and effective federal activities regarding invasive species.
- *NBII invasive species information node (ISIN).* With its partners, this is involved in research projects to understand, document, monitor, predict, and control invasive species.
- *USDA's Animal and Plant Health Inspection Service (APHIS).* This has an invasive species program. USDA also has an invasive-species Web site with links to a number of databases (<http://www.invasivespecies.gov>).

Land and Habitat Use and Management

A NEON observatory dedicated to land and habitat use would have to be structured to allow determination of the local, regional, and continental effects of alternative land and habitat use patterns. Its central focus would be on scaling local effects up to regional or national by linking atmospheric effects and effects of aquatic transport of organisms and materials. Such an observatory could be structured in several ways and would have numerous potential facility needs. At a minimum, it would need a set of nested sites spanning a large geographic range—from midwest croplands, to suburban and urban lands, to the Gulf of Mexico—and a large range of land uses—growing different agricultural crops in different ways, managing pastures and forests in different ways, urban and suburban areas with different types of sewage treatment, and so on.

A wide array of automated sensors would need to be spread across this network of sites, such as

- Instruments designed to monitor concentrations of nitrate, phosphate, and other chemicals in soils of pastures, croplands, forests, and urban and suburban areas.
- Instruments that measure rates of water and material movement into surface water and groundwater; from groundwater to ponds, lakes, streams, and rivers; and from the aforementioned aquatic ecosystems into estuaries, nearshore marine ecosystems, and the open oceans.
- Instruments that measure atmospheric transports that link sites and regions.
- A central facility for data acquisition and informatics that could also serve as a synthesis center.

Some examples of agencies and programs that could collaborate with a land use and habitat management observatory are

- *USDA.* This agency makes estimates for major land use classes across the United States.
- *NOAA's Coastal Change Analysis Program.* A national effort to foster development and distribution of regional landscape cover/change data in the coastal zone through remote sensing technology.

INTEGRATION OF NEON OBSERVATORIES

Each of the six research themes outlined in Chapter 2 addresses a major driver of environmental change. Because these human-driven environmental changes are occurring simultaneously, it is important to understand both the direct effects of each type of environmental change and the interactions among them. That necessitates careful integration of the research among the theme-based NEON observatories. Each of the theme-based observatories should be planned to allow for research focusing on the interactive effects of multiple drivers of environmental change.

With six major challenges, many combinations of drivers could be studied—indeed, too many to study all combinations. For illustrative purposes only, we provide a few examples of cross-cutting research among the six themes. For instance, biodiversity, climate change, and nitrogen deposition may all affect an ecosystem's resistance to biological invasions. Experiments could be designed to assess the interactive effects of these three drivers and test to see whether the interactions were general or differed among regions or ecosystem types. Similarly, landscape changes and climate change might be a driving force for emerging diseases. For example, in the Central Valley of California, about 90% of the wetlands have been converted to agricultural lands and other uses, channeling waterfowls into remaining wetlands. Such mass concentration of birds for prolonged periods facilitates exposure of many birds to disease agents and promotes outbreaks. Research could be conducted to assess the effect of land-use changes on spread of infectious diseases.

The six research themes share some common infrastructure needs. For example, studies of biodiversity, infectious diseases, and invasive species all require sequencing facilities, so that one central sequencing center could be established to serve all observatories. Climate accelerators could serve biogeochemists and climate change scientists and give insights into how climate change would affect the biodiversity and species composition of ecosystems. Eddy flux towers at some sites could be used for both climate-change and biogeochemical research.

Given the overlap between research themes and the shared equipment needs, sites of one theme-based NEON observatory would probably be part of and provide services for several other observatories. Hence, one cost-saving strategy would be to initiate the NEON network with one theme-based observatory and phase in observatories one at a time. When the first national observatory becomes operational, establishment of the second observatory can begin, taking advantage of and leveraging existing facilities in the first observatory. Interdisciplinary research, such as research on the effects of altered carbon or nitrogen availability on shifts in biodiversity, could be pursued in overlapping sites. In addition, the NEON sites with overlapping themes would provide opportunities for scientists from various disciplines to work at the same location and generate synergies of effort. The sequential establishment of theme-based national NEON observatories would facilitate network integration and cross-cutting research.

CHAPTER FOUR

Effect of the National Ecological Observatory Network on the Scientific Community, Education, and Public Outreach

This chapter discusses the potential role of NEON in advancing environmental science, in interdisciplinary training of graduate and undergraduate students, in education of precollege students, and in informing the public about environmental issues.

THE SCIENTIFIC COMMUNITY

Ecology has been evolving from a science dominated by observation to one that combines experimentation with observation to generate models, all in the last 30 years. The resulting advances in our understanding of ecological processes now need to be extended to regional and continental scales to allow the accumulated knowledge to be applied to the nation's most pressing environmental problems. As a first step in extending the spatial scope of environmental research, the scientific community has set up such collaborative or integrative programs as Biodiversity and Ecosystem Processes in Terrestrial Herbaceous Ecosystems and DIVERSITAS but those programs provide little, if any, financial support and no research infrastructure. Centers and programs such as the National Center for Ecological Analysis and Synthesis, the Global Climate Observing System and Global Terrestrial Observing System have been established to facilitate access to environmental data over a large geographic range and thus foster empirical studies on extended spatial scales. However, the data were collected from fragmented research and monitoring programs designed for disciplinary research and regulatory monitoring of specific environments. The next step in expanding the spatial scope of environmental research requires concerted experimental and observational efforts on large spatial and temporal scales. Such studies would require advanced technologies and standardization of equipment and data analysis. NEON would provide the necessary infrastructure to facilitate such an endeavor.

The committee identified three examples that highlight the value of an integrated, collaborative and multidisciplinary approach to ecological research:

- *Long-Term Ecological Research (LTER).* For 20 years, the National Science Foundation has supported a set of research projects dedicated to the execution of long-term observations and experiments that require commitments of resources beyond the timeframe of the project funding cycle of 3-5 years. LTER sites were established through a competitive process, and each site has a program of scientific inquiry that reflects the unique aspects. By establishing a core set of processes that are studied at each site and by developing a network coordinating office, the member sites and the participating scientists can potentially collaborate in cross-site projects. Periodic "all-scientist" meetings provide a forum for presentation of results and development of new collaborative thrusts. Thus, LTER has demonstrated the need for, feasibility of, and potential power of a NEON-like, nationwide network of sites dedicated to research focused on major environmental challenges.
- *AmeriFlux.* The development of the eddy covariance technique for measuring net atmosphere-biosphere exchanges of energy, carbon dioxide, and other materials has revolutionized the field of ecosystem studies in the same way as the implementation of watershed-level experimentation in the 1960s. The value of the method for measuring carbon exchange and its key role in estimating terrestrial regional and global carbon budgets have motivated expansion. Although the resulting

distribution and location of towers have not yet been optimized for continental-scale research, the investigators associated with the sites have joined in a network called AmeriFlux to share information on techniques, compare datasets, and advance the understanding of carbon dynamics in ecosystems. An organization of AmeriFlux investigators that hosts annual meetings has evolved. It has a central scientific office for the dissemination of publications and testing of methods and modeling approaches. The existence of the network has hastened the development and application of an important new technology.

- *Integrative Graduate Education and Research Traineeship (IGERT).* NSF's new IGERT program is relevant to NEON not because of its role in the organization of research efforts, but because of its interdisciplinary team approach designed to foster integrated education across standard disciplines, often at field-station locations. The success of several IGERT projects suggests that advances in graduate training can occur when it is carried out in the framework of large, coordinated research projects. Students in NEON would have similar opportunities.

Although none of those programs offers the large-scale infrastructure and unified national focus that the committee believes should be central goals of NEON, they demonstrate that ecology is ready to use fully the opportunities offered by NEON. NEON would build on those successes and provide a comprehensive examination of basic science, environmental processes and problems, and their effect on biology on a national scale. NEON would enable intellectual and scientific development that is difficult or impossible with the infrastructures available today.

NEON would provide large-scale equipment and infrastructures that are beyond the facilities and budgets of single institutions or even a consortium of universities. Scientists working at NEON observatories could identify areas where the latest technologies are needed. NEON observatories could serve as a platform for testing and implementing new technologies for experimentation and observation. Moreover, NEON scientists could work with researchers of the Center for Embedded Network Sensing (CENS; <http://cens.ucla.edu>)—an NSF science and technology center—to develop sensing systems for large-scale monitoring and data collection. The use of standardized equipment and data analysis would facilitate data-sharing and comparative studies. With a network of infrastructure and an integrated database, NEON could unite scientists across the nation who have common interests and would facilitate interdisciplinary research by linking genome-sequence, functional, ecological, climatic, geographic, and temporal data.

NEON would change how environmental and evolutionary biologists conduct their work by

- Promoting interdisciplinary research.
- Making large-scale hypothesis-testing possible.
- Allowing comparative ecosystem analysis.
- Enabling multiscale research on and monitoring of the propagation of variability across local, regional, and continental scales.

EDUCATION

As stated in Chapter 2, the National Science Board (NSB) has recommended that NSF provide the leadership needed to address the pressing environmental-science education challenges facing the United States. The Belgrade Charter, adopted by a UN conference in 1976, provides a widely accepted international goal for such an endeavor. The goal of environmental education is to develop a world population that is aware of and concerned about the environment and its associated problems. Moreover, the population should have the knowledge, skills, attitudes, motivations, and commitment to work individually and collectively toward solutions of current problems and prevention of new ones (UNESCO-UNEP 1976).

After the Belgrade Charter in 1976, the Tbilisi Declaration—the world's first intergovernment conference on environmental education—established three broad objectives that still provide the foundation for the achievement of the above-stated goal (UNESCO 1978):

- To foster clear awareness of and concern about economic, social, political, and ecological interdependence in urban and rural areas.
- To provide every person with opportunities to acquire the knowledge, values, attitudes, commitment, and skills needed to protect and improve the environment.
- To create new patterns of behavior of individuals, groups, and society as a whole toward the environment.

The established goal and accepted objectives apply to all citizens to different degrees. The level of knowledge and skill required of a scientist is different from that required of an accountant, a teacher, an elementary school student, or a parent. Yet each citizen is entitled to access and training that provide the requisite skills, knowledge, and understandings necessary for informed decision-making, whether those decisions be in the laboratory, classroom, home, or university. NEON would provide a vehicle for such an inclusive education to be fostered and developed. We suggest some ways in which NEON could address diverse educational needs.

Undergraduate and Graduate Education

The importance of NEON observatories for the training of undergraduate and graduate students in interdisciplinary, problem-oriented research was stressed by the participants in the first workshop held to provide advice on NEON's formation and roles (NSF 2000a). They sought programs that would attract graduate students and faculty to courses on research technique and use and on integration of datasets and that would encourage the dissemination of methods, materials, and information into undergraduate and graduate curricula. They could be programs or courses held in the summer, in the academic year, or even over several years (NRC 2001).

Much graduate training is currently centered in relatively narrow, well-defined disciplines. Yet the ecologists and biologists of tomorrow require intensive training and broad knowledge. NEON sites would have graduate students working together who have different early training—in climate, hydrology, biogeochemistry, biodiversity, systematics, spatial analysis, and information technology. Such integration of hands-on experiential learning across normally disparate fields is now possible only on a small scale and only at a few major research universities. NEON would make those opportunities broadly available.

For example, the Biological Collections Institutions envision NEON having a substantial effect on the next generation of taxonomists, systematists, and collection managers. Suggestions include training for the next generation of taxonomists and for parataxonomists, joint teaching opportunities in systematics and "ology" courses, in situ programs for collecting methods and collection management, and development of needed on-line identification tools to hasten field and laboratory identification (NSF 2002b).

The links across the science, technology, and mathematics disciplines are becoming deeper and more extensive. Yet as we point out in Chapter 2, a National Research Council report (2003a) noted that undergraduate biology education has "changed relatively little during the past two decades" and that "the ways in which most future biologists are educated are geared to the biology of the past, rather than to the biology of the present or future." Such programs as the nationwide Research Experiences for Undergraduates and the Undergraduate Research Opportunities Program aimed at minority students begin to address the need, but the latter program exists at few universities, and both touch the lives of few students. NEON has the potential to engage undergraduates in interdisciplinary research on a broad scale.

Laboratories provide the ideal opportunity for undergraduate students to experience interdisciplinary research and confront real-world scientific investigations and problems. In re-examining undergraduate curricula in light of current research needs, NEON observatories would lead the way, presenting examples of current research that exemplify how science consists of unanswered questions and providing extended research-based opportunities for students to ask questions, make observations, analyze data, experience teamwork, work with mentors, and obtain a real-world view of the life of an interdisciplinary researcher (NRC 2003a).

Precollege Education

The National Research Council, the American Association for the Advancement of Science, the National Science Teacher's Association, and others recommend inquiry as the technique, method, or process by which the goals of learning can be addressed. Inquiry is a way of learning that involves making observations; asking questions; examining information to determine what is already known; using tools to gather, analyze, and interpret data; suggesting answers, explanations and predictions; and finally communicating results (NRC 1996). A NEON site is an ideal environment and location for students to engage in environmental-science inquiry and to gather, interpret, and analyze data alongside scientists who are engaged in the same authentic activities.

Starting inquiry-based experiences at the beginning of a student's K-12 education is important for long-term success. In 1997, the National Research Council released *Introducing the National Science Education Standards, Booklet* which emphasizes inquiry-based processes for K-12 students. The standards define what all students should know and be able to do, detail the teaching and professional-development strategies necessary to deliver this high-quality science content, and provide guidelines for assessing the degree to which the standards have been achieved (NRC 1997). The standards provide a roadmap for science literacy, and each state has developed its own set of statewide science standards based on the national goals.

Several standards-based, inquiry-driven educational projects now under way provide models for the NEON sites. For example, the Global Learning and Observations to Benefit the Environment program provides opportunities for students to conduct valuable scientific work, analyze the results and use advanced technologies. Students also have the opportunity to communicate with others nationally and internationally. The work of the students, teachers, and scientists as they study the global environment is coordinated by the University Corporation for Atmospheric Research in partnership with Colorado State University under a cooperative agreement awarded by the National Aeronautics and Space Administration.

Another example is the Central Arizona-Phoenix Long-Term Ecological Research (CAPLTER) project, which engages students and teachers across the Phoenix metropolitan area in the collection of data on plants, birds, and insects to determine the effects of urbanization on their local ecosystem. Project data are entered into the CAPLTER database, thereby vastly expanding its coverage. Since 1999, the program has involved 77 teachers in 59 schools at grades 4-10. Those schools are meeting their inquiry-based standards requirements while CAPLTER is receiving data and fulfilling its educational mission. CAPLTER also works with the local school district in summer institutes, workshops, and mentoring for teachers (NRC 2003b). NEON could use those programs as examples of K-12 student and teacher education.

For students to understand inquiry, teachers need to be well-versed in inquiry-based methods. However, few teachers have the opportunities to learn science through inquiry or to conduct scientific inquiries themselves (NRC 2000). Immersion has emerged as one of the key strategies for the professional learning of teachers. Immersion experiences often occur in laboratories where teachers join scientists to conduct science in a real-world setting. The outcome of such long-term, in-depth learning is a change in teachers' conceptions of the very nature of science and an understanding that science teaching is less a matter of knowledge transfer and more a process by which knowledge is generated. NEON observatories could provide a venue for science training of K-12 teachers. The Department of Energy's Teacher Research Associates program is a good example of an 8-week immersion experience for high school teachers (Loucks-Horsley et al. 1998).

Informal Education

Both NSB and the President's Committee of Advisors on Science and Technology (PCAST) panel recommend an increased focus on informal education as an effective tool for increasing environmental literacy (PCAST 1998, NSB 2000). PCAST states that informal education is very cost-effective and people enjoy learning informally when they have control over the timing and content. Chicago Wilderness is given as an example: over 160 agencies, organizations, institutions, and local governments working together to restore, maintain, and increase the biodiversity of the Chicago region. The consortium is combining and integrating its education and research efforts in the member institutions and in coordinated programs for the general public focused on local natural science. Displays, exhibits, weekend programs, volunteer opportunities, training, a magazine, and a Web site are some of the informal coordinated educational efforts targeted to the 8 million people in the Chicago metropolitan area (PCAST 1998). Such an informal coordinated education program should be central to every NEON observatory.

NSB encourages NSF to support many more environmental-education efforts through informal venues—museums, aquariums, zoos, nature centers, television, and other learning modes attractive to the public, such as radio programs and Web sites. Relating such programs to citizens' personal, community, and work lives could be a way to increase the public's ability to deal with complex environmental issues (NSB 2000). NEON observatories, through their partnerships with other agencies and with their regional and continental focus, could provide an ideal opportunity for the successful implementation of the NSF directive. Informal partners of NEON consortia, especially science and natural-history museums, constitute rich resources for the public's understanding of science and ways to build bridges between scientific research and the public.

PUBLIC OUTREACH AND INVOLVEMENT

Citizen science has become an important involvement and data-collection strategy in the United States. The Cornell Laboratory of Ornithology has created a vast citizen-science network for collection of bird data; adults and students collect and submit volumes of information on backyard feeders, schoolyard watches, and specific species (such as house finches, pigeons, and birds of prey). The Illinois Department of Natural Resources trains citizen-scientists to collect targeted data on wetlands, rivers, prairies, forests, and even urban green spaces through its EcoWatch Program. The second NEON workshop suggested that such citizen-science monitoring could be done at NEON observatories. Participants suggested a host of on-site education programs similar to those listed above on informal education to increase citizen involvement and understanding (NSF 2000b). Such a monitoring program would contribute to collection of information and would increase citizens' awareness of research programs.

To disseminate and provide access to information synthesized from research observations, NEON could set up a Web site similar to that of Earthscope (*http://www.earthscope.org/*). The Web site would provide not only an overview of NEON programs, but also a summary of key scientific findings written for a lay audience and access to environmental data collected by NEON that could be used in a classroom or for making informed policy decisions.

NEON also presents an excellent opportunity to include under-represented communities in its outreach and community-involvement efforts. Members of minority groups, and professionals in journalism, agriculture, forestry, ranching, and business could all be informed by targeted outreach. The American Institute of Biological Sciences white paper on NEON suggests that each NEON observatory have a funded outreach office to promote such public inclusion. The office would interact with broadcast and print media, develop articles for press releases and magazines, promote coverage on radio and television, publish newsletters, and develop a public Web site. Additional public programs have been suggested such as tours, open houses, activity days, and docent and volunteer programs (AIBS 2003).

CHAPTER FIVE

A Synthesis of Early Concepts of the National Ecological Observatory Network and a New Vision

The committee strongly endorses NEON and suggests some refinement of its implementation plan to ensure that it would provide the necessary infrastructure efficiently for effective large-scale environmental research.

The National Science Foundation (NSF) sponsored six workshops to outline detailed features of the National Ecological Observatory Network (NEON) (NSF 2000 a,b,c, 2002 a,b,c). The American Institute of Biological Sciences (AIBS) then prepared an overview report (AIBS 2003). In addition, as noted earlier in this report, NSF included a summary of its vision of NEON in its FY2003-2004 budget request (<http://www.nsf.gov/bio/bio_bdg04/neon04.htm>) and published a detailed overview (NSF 2002d). The committee used those documents and comments from various NSF officials, other speakers at its public meeting, and participants in its Web forum to build a picture of potential NEON designs, how they might be implemented, and how NEON might address key challenges in ecological and environmental science on a regional to continental scale. In doing so, the committee focuses on what it feels are the major issues facing NEON. In this chapter, we do not discuss many of the minor inconsistencies that unavoidably occurred when six groups of scientists—

each group chosen to represent a different part of the discipline—offered their views of NEON. Moreover, unlike the AIBS report, which was commissioned to synthesize the six workshops, our report is to evaluate the conceptual foundations of a NEON-like network and to determine whether NEON as currently conceived would provide the infrastructure and logistical support needed to address ecological and environmental questions of national concern. To evaluate a program as large and complex as NEON, the committee assessed the ideas proposed in the workshops and the synthesis of those ideas put forward by NSF (NSF 2002d) and AIBS (AIBS 2003) and compared them with alternative approaches to the implementation of NEON. We address that task in this chapter.

Many excellent recommendations were presented in the six workshops, but a single unified concept of NEON did not emerge, largely because not all statements and visions of NEON's potential structure are compatible. That is probably a result of the organization of the workshops, which each brought together one branch of the scientific community to formulate individual viewpoints on the NEON concept. As stated in Chapter 3, the differences and conflicts between ideas described in the workshops make the evaluation of the third question in the committee's charge difficult to answer: "Will NEON, as conceptualized in the series of six community workshops, be able to provide infrastructure and logistical support to address the ecological and environmental questions of national concern?" We document here some of the major differences among the publications about NEON and provide an evaluation of the concept of NEON that is relevant to the third question in our charge.

An example of differing or conflicting ideas about NEON is the different published descriptions of the overall mission of NEON. The AIBS report (AIBS 2003), the NSF FY2003-2004 budget request (<http://www.nsf.gov.bio.bio_bdg04/neon04.htm>), and the 2002 NSF summary of NEON (NSF 2002d) all paint NEON with slightly different colors. They all describe important parts of the NEON vision, but they also reflect the different foci of the different types of scientists at the workshops. Thus, it is not surprising that the reports do not speak with a single voice.

NSF's synthesis of those documents states that "collectively, the network of observatories will allow comprehensive, continental-scale experiments on ecological systems and will represent a virtual laboratory for research to obtain a predictive understanding of the environment." Such observatories, at which coordinated data collection and ecological experiments could be conducted, was universally lauded by the federal agencies and scientific societies represented at the public workshop and Web forum (see Appendix C).

In March 1997, the Committee on Environment and Natural Resources of the National Science and Technology Council proposed a framework for "Integrating the Nation's Environmental Monitoring and Research Networks and Programs." Its report made a strong case:

> A fundamental improvement in the way that the United States monitor its environment is required if we are to meet the challenges facing us during the next several decades. Current monitoring programs do not provide integrated data across multiple natural resources at the various temporal and spatial scales needed to develop policies based on current scientific understanding of ecosystem processes. . . . [In fiscal year 1995, . . . about $650 million] was focused on activities in about 30 major Federal environmental monitoring and research networks and programs. Although the associated programs, activities, and networks were established in response to specific legislation about specific resources and issues, they can be better integrated to provide information needed for effective ecosystem management. Similarly, the networks can be better integrated to provide information synthesis across a range of spatial scales.

Later report by the Heinz Center (Heinz Center 2002) titled *The State of the Nation's Ecosystems* indicated that relevant datasets were still not integrated and that many data gaps existed:

> In seeking data, we found a classic case of a glass that is both half empty and half full. In applying the selection criteria outlined

> above, we found adequate data for more than half of the selected indicators, with trends or other context information on many of these, allowing us to report meaningfully on many aspects of ecosystem condition. However, substantial gaps remain, and until and unless these gaps are filled, Americans will not have access to a complete picture of the "state of the nations' ecosystems."

NSF's general concept of NEON would to some extent address those monitoring issues, but NSF's vision focuses NEON more strongly on helping ecology to become a predictive science. We acknowledge that more-thorough and well-coordinated national environmental monitoring is needed, but we conclude that the resources available to NSF would be unable to fill the many identified gaps in national environmental monitoring (Heinz Center 2002) and that monitoring itself is less compatible with the mission of NSF, which is to advance mechanistic understanding and predictive ability in environmental science. Thus, we strongly support NSF's vision that NEON's central role should be to facilitate experimentation and observation for the advancement of environmental science.

Although the committee was not charged to provide a complete design and implementation plan for NEON, we offer here a few suggestions designed to help NEON to achieve the potential articulated in NSF's vision. The suggestions contain elements that flow from the work of all six workshops. For instance, the overall structure of NEON as a set of spatially distributed sensor arrays and experimental sites emerges from all the workshop reports. However, we also evaluate potential alternatives for the structure and development of NEON in our assessment of whether NEON could provide the infrastructure and logistical support needed to address environmental challenges. Major differences are highlighted below, and they are discussed briefly in the context of each workshop report.

1. Physical structure of a NEON observatory: Each NEON observatory was envisioned as a core and associated satellite sites in a given region (biome type) of the nation. Such observatories were to be linked to form a single NEON network that spanned the continent.

Suggested alternative: Each observatory should focus on a major environmental challenge instead of a single biome and have multiple sites providing a continentwide scope. The sites that constitute a NEON observatory should be selected simultaneously so that they can address optimally the major environmental challenges that the nation faces.

2. Observatory number and placement: Many documents on NEON (NSF 2002d, AIBS 2003) discussed the possibility of having 16 regional observatories in North America based on a Forest Service designation of 16 biomes in the coterminous United States. Establishing observatories based on terrestrial ecoregions fails to acknowledge that freshwater and marine ecoregions are also of national importance. Furthermore, ecoregions vary greatly in size, and some may have little relevance to some environmental challenges.

Suggested alternative: Each observatory should focus on a central research theme and contain sites—whether terrestrial, freshwater, or marine—that are most relevant to that theme. We suggest a few criteria for site selection of a theme-driven observatory.

- Geographic distribution and coverage.
- Integration of existing facilities.
- Flexibility to accommodate other research themes and to be expanded to meet future demands.

3. Growth of the network: NSF envisioned that NEON could grow from two regional observatories until it met its purpose of providing integrated data on the state and function of ecosystems in the United States. However, the planning documents provide little information for how NEON should grow, except that the network would grow via selection of the best sites through a competitive review similar to that used for selection of the current Long-Term Ecological Research (LTER) sites. However, the differences in goals between NEON and the LTER sites suggest that site selection for NEON should grow in a different way—especially because NEON sites need to function in an integrated network and LTER sites are meant to function independently. Initiating the NEON network with two sites in different biomes, as planned by NSF, cannot immediately fill the national need for integrated ecological data.

Suggested alternative: The network should be designed in such a way that even the first elements are built to fulfill the national networking role. Each observatory would focus on a key environmental challenge and would be built with continentwide capacity to allow understanding of key environmental issues on a scale appropriate to national-level problems. The network could be initiated as one theme-driven observatory with sites across the nation. Growth of the network would occur as each new theme-oriented national observatory was built and set up to focus on additional issues. New observatories would use some of the facilities of former ones but probably would require serial investment in infrastructure.

4. Funding: Funding to establish each individual observatory was estimated at $20 million for construction plus about $3 million in operation and maintenance costs. Budget development focused on the individual observatory and did not address the funding requirements for network-level administrative support and equipment, such as bio-informatics synthesis centers or centers of taxonomic expertise. Individual NEON projects were to be funded through NSF's competitive proposal program, but it was not clear how core data collection and analysis would be funded.

Suggested alternative: Funds for observatory infrastructure—facilities, equipment, data and sample repositories—should come from Major Research Equipment and Facilities Construction (MRFEC) account, and the amount of funds should reflect the demands of the overall mission of the NEON observatory, not a planned funding formula. Depending on the theme of the observatory, construction and maintenance costs could exceed $20 and $3 miilion, respectively. Insufficient funding for construction and equipment acquisition could hinder NEON's ability to achieve its goal of providing nationwide infrastructure to address continental-scale questions. In addition, operational funds and funds for individual research projects to be implemented within each observatory should be made available by NSF. Research funds could be made available through relevant existing programs or through a new program designed for large-scale interdisciplinary research.

5. Informatics and synthesis: An informatics infrastructure was seen to be critical to NEON's success, but no firm plans for the integration of different data streams or analyses have been articulated. The informatics and synthesis center would ensure efficient data-sharing and data-archiving. Furthermore, information collected from NEON observatories could be disseminated for education purposes via the bioinformatics and synthesis center.

Suggested alternative: Informatics and synthesis center is a pivotal part of the basic NEON plan. Bioinformatics tools and experts would be needed to develop new mathematical algorithms to decipher and interpret large data streams. NEON should explore the latest applications of data assimilation technologies (for example, four dimensional data assimilation). Its bioinformatics center could either partner with or be modeled after existing bioinformatics centers such as the National Institutes of Health's National Center for Biotechnology Information which manages GenBank, the National Center for Ecological Analysis and Synthesis, or the National Biological Information Infrastructure. The envisioned informatics center could also include systematics data on the nation's biodiversity and explore how modern informatic tools can speed their identification and documentation.

6. Governance: It was envisioned that NEON would be governed by several committee groups with responsibility for different aspects, such as informatics and facility and program evaluation. Both centralized and decentralized approaches were proposed in the workshops, possibly because some workshop groups were not aware of the management requirements for MREFC. The proposed operational governance structure may result in a large bureaucracy that would hinder NEON operations, rather than help. Although different suggestions were put forward on NEON guidance, no groups specified how the governing body or bodies would be supported and funded. To determine the success and effects of NEON, it was recommended that NEON be evaluated at both the observatory level and the network level. The third workshop developed evaluation criteria for individual observatories, and for the network as a whole (NSF 2000c). An individual observatory would be evaluated with respect to such items as use by the scientific community, quality of the research, ability to attract high-quality users, and access to data. Network-level review would look at the gains achieved in science, technology, data, education, and process.

Suggested alternative: The committee endorses NSF's proposal of a NEON coordinating unit to oversee the implementation and operation of NEON and to ensure integration of observatories. We recommend a single scientific oversight committee, preferably formed by a neutral body, such as a multiuniversity consortium. The committee would work with NSF to ensure that adequate resources are available to sustain NEON operation and that the goals of NEON are met. The committee would also solicit input from the broad scientific community for designs and improvement of NEON to ensure its effectiveness.

7. Education and outreach: NEON would present unprecedented opportunities for education and outreach and for conveying the value and relevance of environmental biology research to a large audience. NEON observatories were to communicate information to the scientific community, to local, regional and national decision-makers, to the general public, and to the full range of students, from kindergarten to graduate students. The committee agreed with those goals but found few details on how education and outreach goals would be achieved and who might be responsible for carrying out the plans.

Suggested alternative: Multiple systematic educational programs should be integrated into NEON's plan so that program plans and facilities for education and outreach would be included from the inception of each observatory.

8. Partnerships: NEON would involve extensive partnering and collaboration among many, often disparate, groups. The inclusion of other government agencies already involved in scientific research, networking, land management, and so on was specifically recommended. However, there was no discussion of how or when it might be achieved. A review of all workshop participants also showed an absence of representatives of federal agencies.

Suggested alternative: The next phase of NEON planning and development should include plans for partnerships and collaboration with other federal agencies. Establishing memoranda of understanding is one way to facilitate collaboration. Such issues as access to facilities, standardization of data collection, access to data and research coordination should be discussed.

Although the committee proposes modification of the NEON implementation plan, it agrees with the fundamental concept of NEON as stated by NSF and with most of the recommendations derived from the six workshops. The committee hopes that its suggestions will help fill the gap between the NEON mission and the implementation plan that emerged from the workshops to fulfill the requirements of the MREFC program.

The workshops provided crucial documentation and careful consideration of essential building blocks from which a focused vision could emerge. The documents included fundamental insights into how and why a NEON network should function. By consideration of all available material, the committee tried to extract the best ideas from the disparate set of recommendations and then focused and refined them to propose a new, better-targeted, more-integrated vision for NEON.

CHAPTER SIX

Findings and Recommendations

Drawing on the reports of past workshops on the National Ecological Observatory Network (NEON), on the synthesis of those reports by the National Science Foundation (NSF) and the American Institute of Biological Sciences, on the National Research Council report on *Grand Challenges in Environmental Science* and on the expertise of its own members, the committee identified six large-scale environmental issues of national concern. It then examined NSF's conception of NEON and assessed whether NEON's national network of field and laboratory research infrastructure would be an appropriate and necessary means of addressing those large-scale issues. The effect that NEON may have on the scientific community and on the next generation of scientists was also assessed. The committee's findings and recommendations are summarized below.

Finding 1

The committee identified six critical environmental challenges that are regional, continental, or global in their extent—biodiversity, species composition, and ecosystem functioning; ecological aspects of biogeochemical cycles; ecological implications of climate change; ecology and evolution of infectious diseases; invasive species; and land use and habitat alteration. Although all six issues are of national concern, at present we do not have knowledge adequate to address them. Rapid and substantial advances in basic scientific knowledge would be needed for society to deal with those major environmental issues wisely.

Recommendation 1

The committee strongly recommends that the nation and NSF give highest priority to research on the six environmental challenges the committee identified.

Finding 2

An in-depth understanding of the causes and consequences of the six challenges is needed to allow assessment of potential ecosystem response and to formulate effective environmental policy. Meeting this need would require large-scale experimentation, long-term observation, and scientific synthesis that could be carried out only using a network of nationwide infrastructure and research sites that are optimized for the purpose.

Recommendation 2

The committee strongly endorses a NEON-like endeavor and the vision of the mission of NEON that NSF has articulated. As proposed by NSF, the central goal of NEON would be to perform comprehensive, continental-scale experimental and observational research on the nation's ecological systems to obtain an in-depth understanding of the environment. That knowledge could serve as a basis for developing predictive capability and would allow assessment of how alternative societal actions and policies will affect species and ecosystems and the services that they provide to society.

Finding 3

NEON, as currently proposed, would be built piecemeal via funding of one or two regional observatories at a time, and each observatory would be managed by a different university or consortium. Such a design and implementation might hinder the integration and the national nature of the network of sites and make it less than optimally effective in facilitating coordinated continental-scale research.

Recommendation 3

Each NEON observatory should be initiated as a nationwide network of facilities and infrastructure designed for a coalition of many multi-investigator, multi-disciplinary teams from across the nation to address optimally one of the six major environmental challenges. Each observatory should accommodate a combination of experimentation and observation and should comprise a collection of nationwide sites—whether terrestrial, freshwater, or marine—that are most relevant to its central theme. Sufficient funds must be allocated for the development of each NEON observatory as a nationwide network. Because the six research themes identified by the committee have overlapping infrastructure needs, complete construction of each observatory could successively build on sites and infrastructure as each one is established. Each later observatory could leverage investments made in the existing ones; this would increase the effectiveness and decrease the cost of the entire network.

Finding 4

The committee agrees with the fundamental concept of NEON as stated by NSF and with many of the major recommendations derived from the six workshops. It believes that NEON would provide opportunities for large-scale environmental research and enable intellectual and scientific development that is impossible with existing infrastructure. However, the effective implementation of NEON and the maximization of its contributions to science and the nation require a refined focus and a more detailed plan for its implementation.

Recommendation 4

The creation of a NEON observatory addressing one of the six major environmental challenges would probably be a multistep process involving open workshops and working groups on that challenge, peer-reviewed preproposals submitted by different teams for work on that challenge at particular sites, and discussion and coordination among the chosen teams to synthesize the diverse ideas generated and create final plans for the entire observatory. The goals of the multistep process are to optimize the ability of various scientists to contribute creativity and personal commitment to the observatory and the ability of the multiple teams and sites to pursue their shared challenge in a coordinated manner. The result would be a clear vision of what the observatories are intended to look like and achieve, which would additionally provide a better fit within the purview of Major Research Equipment and Facilities Construction funding. The committee offers some specific suggestions:

- NSF should encourage NEON observatories to form partnerships with existing informatics centers (for example, the National Center for Ecological Analysis and Synthesis, the National Biological Information Infrastructure and GenBank) or use them as models.
- Each NEON observatory should form partnerships with appropriate federal, state, and local agencies and organizations to coordinate

and optimize data collection and sharing. Establishing memoranda of understanding could facilitate partnerships and collaboration.

- The committee endorses NSF's proposal of a coordinating unit to oversee the implementation and operation of NEON. It recommends that a single scientific coordinating unit, preferably formed by a neutral body such as a multiuniversity consortium, provide this oversight.

Finding 5

The challenge of educating the next generation of scientists, teachers, and students and of reaching out to the public about environmental science and issues cannot be met casually by individual researchers. Nothing short of an integrated, sequenced education and outreach plan that meets national standards, targets audience needs, and is based on measurable outcomes will answer the leadership and education vision set forth to NSF by the National Science Board. The NEON observatories are ideal venues for such an integrated, robust education and outreach plan.

Recommendation 5

NEON's education programs should be targeted at undergraduate and graduate students and faculty, precollege students and teachers, and informal education, and citizen outreach. We recommend that multiple, systematic programs be integrated into the NEON proposal and developed, sequenced, and planned beginning at each observatory's inception and with attendant funding mechanisms and budgets.

If implemented in the general format outlined above, NEON could provide the fundamental scientific advances needed to understand how human-induced environmental change influences the long-term quality of life and wealth creation for the nation. Long-term outputs would include a science-based approach to environmental policy, risk analysis for environmental threats, evaluation of potential approaches to the threats, and a venue for increasing public awareness and understanding of environmental issues. NEON could revolutionize the discipline of environmental biology by transforming ecology into a more mechanistic science that generates predictions and solutions that would help society to deal actively with major environmental issues.

References

AAAS (American Association for the Advancement of Science). 1989. Science for All Americans. Washington, DC: American Association for the Advancement of Science.

AIBS (American Institute of Biological Sciences). 2003. Rationale, Blueprint, and Expectations for the National Ecological Observatory Network. Washington, DC: American Institute of Biological Sciences.

Anderson, P.K., and F.J. Morales. 1994. The emergence of new plant diseases: the case of insect-transmitted plant viruses. *Annals of the New York Academy of Sciences* 740:181-194.

Avissar, R., and R.A. Pielke. 1989. A parameterization of heterogeneous land surfaces for atmospheric numerical-models and its impact on regional meteorology. *Monthly Weather Review* 117(10):2113-2136.

Carpenter, S.R., W.A. Brock, and P.C. Hanson. 1999. Ecological and social dynamics in simple models of ecosystem management. *Conservation Ecology* 3(2):4.

Clark, J.S., S.R. Carpenter, M. Barber, S. Collins, A. Dobson, J.A. Foley, D.M. Lodge, M. Pascual, R. Pielke Jr., W. Pizer, C. Pringle, W.V. Reid, K.A. Rose, O. Sala, W.H. Schlesinger, D.H. Wall, and D. Wear. 2001. Ecological forecasts: an emerging imperative. *Science* 293:657-660.

Daszak, P., A.A. Cunningham, and A. D. Hyatt. 2000. Emerging infectious diseases of wildlife—Threats to biodiversity and human health. *Science* 287:443-449.

Downing, J.A., J.L. Baker, R.J. Diaz, T. Prato, N.N. Rabalais and R.J. Zimmerman. 1999. Gulf of Mexico Hypoxia: Land and Sea Interactions. Task Force Report No. 134. Ames, IA: Council for Agricultural Science and Technology (CAST).

Gardner, R.H., W.M. Kemp, V.S. Kennedy, and J.E. Petersen. 2001. Scaling Relations in Experimental Ecology. New York: Columbia University Press.

Gould, E.A., X.D. Lamballerie, P.M.D.A. Zanotto, and E.C. Holmes. 2001. Evolution, epidemiology and dispersal of flaviviruses revealed by molecular phylogenies. *Advances in Virus Research* 57:71-103.

Haddad, N.M., D. Tilman, J. Haarstad, M. Ritchie, and J.M.H. Knops. 2001. Contrasting effects of plant richness and composition on insect communities: a field experiment. *The American Naturalist* 158:17-35.

Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, J. Lerner, and R. Ruedy. 1984. Climate sensitivity: Analysis of feedback mechanisms., in J. E. Hansen, and T. Takahashi (eds.), *Climate Processes and Climate Sensitivity*. Pp. 130-163. Washington, DC: American Geophysical Union.

Hector, A., B. Schmid, C. Beierkuhnlein, M.C. Caldeira, M. Diemer, P.G. Dimitrakopoulos, J. Finn, H. Freitas, P.S. Giller, J. Good, R. Harris, P. Högber, K. Huss-Danell, J. Joshi, A. Jumpponen, C. Körner, P.W. Leadley, M. Loreau, A. Minns, C.P.H. Mulder, G. O'Donovan, S.J. Otway, J.S. Pereira, A. Prinz, D.J. Read, M. Scherer-Lorenzen, E.-D. Schulze, A.-S.D. Siamantziouras, E.M. Spehn, A.C. Terry, A.Y. Troumbis, F.I. Woodward, S. Yachi, and J.H. Lawton. 1999. Plant diversity and productivity experiments in European grasslands. *Science* 286:1123-1127.

Heinz Center. 2002. The State of the Nation's Ecosystems. New York: Cambridge University Press.

Houghton, R.A., J.L. Hackler, and K.T. Lawrence. 1999. The U.S. carbon budget: contributions from land-use change. *Science* 285:574-578.

Institute of Medicine (IOM). 2002. The Emergence of Zoonotic Disease. Understanding the Impact on Animal and Human Health. Washington, DC: National Academy Press.

Intergovernmental Panel on Climate Change (IPCC). 2001a. Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. In J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (eds.). Cambridge, UK and New York, NY, USA: Cambridge University Press.

IPPC. 2001b. Climate Change 2001: Impacts, Adaptation, & Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. In J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White (eds.). Cambridge, UK: Cambridge University Press.

Koster, R.D., and M.J. Suarez, 1995. Relative contributions of land and ocean processes to precipitation variability, *Journal of Geophysical Research* 100 (D7):13775-13790.

Loreau, M., S. Naeem, P. Inchausti, J. Bengtsson, J.P. Grime, A. Hector, D.U. Hooper, M.A. Huston, D. Raffaelli, B. Schmid, D. Tilman, and D.A. Wardle. 2001. Biodiversity and ecosystem functioning: current knowledge and future challenges. *Science* 294:804-808.

Loucks-Horsley, S., N. Love, K.E. Stiles, S. Mundry, and P.W. Hewson. 1998. Designing Professional Development for Teachers of Science and Mathematics. Thousand Oaks, CA: Corwin Press, Inc.

Lubchenco, J., A.M. Olson, L.B. Brubaker, S.R. Carpenter, M.M. Holland, S.P. Hubbell, S.A. Levin, J.A. Macmahon, P.A. Matson, J.M. Melillo, H.A. Mooney, C.H. Peterson, H.R. Pulliam, L.A. Real, P.J. Regal and P.G. Risser. 1991. The sustainable biosphere initiative: an ecological research agenda. *Ecology* 72(2):371-412.

Mitchell, C.E., D. Tilman, and J.V. Groth. 2002. Effects of plant species diversity, abundance, and composition disease. *Ecology* 83(6):1712-1726.

Naeem, S., K. Håkenson, J.H. Lawton, M.J. Crawley, and L.J. Thompson. 1996. Biodiversity and plant productivity in a model assemblage of plant species. *Oikos* 76:259-264.

NEETF (National Environmental Education and Training Foundation). 1997. National Report Card on Environmental Knowledge, Attitudes and Behaviors.

NEETF. 1998. National Report Card on Environmental Knowledge, Attitudes and Behaviors.

NEETF. 1999. The National Report Card on Environmental Readiness for the 21st Century.

NRC (National Research Council). 1996. National Science Education Standards. Washington, DC: National Academy Press.

NRC. 1997. Introducing the National Science Education Standards, Booklet. Washington, DC: National Academy Press.

NRC. 2000. Inquiry and the National Science Education Standards: A Guide for Teaching and Learning. Washington, DC: National Academy Press.

NRC. 2001. Grand Challenges in Environmental Sciences. Washington, DC: National Academy Press.

NRC. 2002. Community and Quality of Life. Data needs for informed decision making. Washington, DC: National Academy Press.

NRC. 2003a. BIO 2010: Transforming Undergraduate Education for Future Research Biologists. Washington, DC: The National Academies Press.

NRC. 2003b. Biocomplexity Investigators Explore the Possibilities: Summary of a Workshop Integrating Research and Education. Washington, DC: The National Academies Press.

NSB (National Science Board). 2000. Environmental Science and Engineering for the 21st Century: The Role of the National Science Foundation. Arlington, VA: National Science Foundation.

NSF (National Science Foundation). 2000a. Report on First Workshop on the National Ecological Observatory Network, held January 10-12 at Archbold Biological Station, Lake Placid, FL. Arlington, VA: National Science Foundation.

NSF. 2000b. Report to National Science Foundation from the Second Workshop on the Development of a National Ecological Observatory Network (NEON), held on March 9-13 at San Diego Supercomputer Center, La Jolla, CA. Arlington, VA: National Science Foundation.

NSF. 2000c. Report to National Science Foundation from the Third Workshop on the Development of a National Ecological Observatory Network (NEON), held on May 3-4, 2000 at Sante Fe Institute, Santa Fe, NM. Arlington, VA: National Science Foundation.

NSF. 2002a. Report to the National Science Foundation from the Fourth Workshop on the Development of a National Ecological Observatory Network (NEON): Standard Measurements and Infrastructure Needs, held on June 4-5, 2002 at the Millenium Hotel, Boulder, CO. Arlington, VA: National Science Foundation.

NSF. 2002b. Final Report on NEON-V: CRIPTON Workshop, held on June 14-16, 2002 at Field Museum of Natural History, Chicago, IL. Arlington, VA: National Science Foundation.

NSF. 2002c. Report to the National Science Foundation from the Sixth Workshop of a National Ecological Observatory Network (NEON): Information Management, held on September 16-18 at the National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, CA. Arlington, VA: National Science Foundation.

NSF. 2002d. National Ecological Observatory Network. Arlington, VA: National Science Foundation.

NSF. 2002e. Facilities Management and Oversight Guide. Arlington, VA: National Science Foundation.

Parmesan, C., and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts in natural systems. *Nature* 421:37-42.

PCAST (President's Committee of Advisers on Science and Technology. 1998. Teaming with Life: Investing in Science to Understand and Use America's Living Capital. Washington, DC: Office of Science and Technology Policy.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. *BioScience* 50:53-65.

Postel, S. 1999. *Pillar of Sand: Can the Irrigation Miracle Last?* New York: W.W. Norton & Company.

Randolph, S.E., R.M. Green, M.F. Peacey, and D. J. Rogers. 2000. Seasonal synchrony: the key to tick borne encephalitis foci identified by satellite data. *Parasitology* 121:15-23.

Rogers, D.J., S.E. Randolph, S.W. Lindsay, and C.J. Thomas. 2001. Vector-borne diseases and climate change. Pp. 101-138 in R. Maynard (ed.), *Health Effects of Climate Change in the UK*. Leicester, UK: Institute of Environment and Health.

Schindler, D.W. 1999. From acid rain to toxic snow. *Ambio* 28:350-355.

Stachowicz, J.J., R.B. Whitlatch, and R.W. Osman. 1999. Species diversity and invasion resistance in a marine ecosystem. *Science* 286:1577-1579.

Taylor L.H., S.M. Latham, and M.E. Woolhouse. 2001. Risk factors for human disease emergence. *Philosophical Transactions of the Royal Society of London (Series B Biological Sciences)* 356:983-989.

Tilman, D., D. Wedin, and J. Knops. 1996. Productivity and sustainability influenced by biodiversity in grassland ecosystems. *Nature* 379:718-720.

Tilman, D., P. B. Reich, J. Knops, D. Wedin, T. Mielke, and C. Lehman. 2001. Diversity and productivity in a long-term grassland experiment. *Science* 294:843-845.

Torchin, M.E., K.D. Lafferty, A.P. Dobson, V.J. McKenzie, and A.M. Kuris. 2003. Introduced species and their missing parasites. *Nature* 421:628-630.

UNESCO. 1978. Final Report: Intergovernmental Conference on Environmental Education. Tbilisi, USSR: UNESCO.

UNESCO-UNEP. 1976. Connect: UNESCO-UNEP Environmental Education Newsletter. UNESCO-UNEP.

Vitousek, P. M. 1994. Beyond global warming: ecology and global change. *Ecology* 75:1861-1876.

Vitousek, P. M., J.D. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger and D. Tilman. 1997. Human alteration of the global nitrogen cycle: sources and consequences. *Ecological Applications* 7:737-750.

World Health Organization (WHO). 1959. Zoonoses. Second report of the Joint WHO/FAO Expert Committee. Geneva, Switzerland: World Health Organization.

APPENDIX A

Committee on the National Ecological Observatory Network Biographical Sketches

Chair **G. David Tilman** is Regents Professor and director of the Cedar Creek Natural History Area at the University of Minnesota. He received his PhD in 1976 from the University of Michigan. His honors include Guggenheim Fellow (1984), Fellow of the American Academy of Arts and Sciences (1995), Pew Scholar in Conservation Biology (1995), and the Ecological Society of America's Cooper (1989) and MacArthur (1996) Awards. He is a member of the National Academy of Sciences, the Board on Environmental Studies and Toxicology, and the Proceedings of the National Academy of Sciences Editorial Board. His field experiments and theory explore how competition, biodiversity and global change drivers influence community and ecosystem patterns and processes. In 2001 he was designated the most highly cited environmental scientist for the decade (1990-2000) by the Institute for Scientific Information.

John D. Aber is professor and director of the Complex Systems Research Center at the University of New Hampshire. He received his BS in Engineering and Applied Science, and MS and PhD in forestry and environmental studies from Yale University. His work focuses on ecosystem modeling of the effects of environmental factors on forest production and nutrient cycling. He is particularly interested in nitrogen cycling and the process of nitrogen saturation in forests in response to acid deposition. Dr. Aber has served as an associate editor for *Biogeochemistry*, *Trees: Structure and Function*, the Canadian Journal of Forest Research, and the *Journal of Near Infrared Reflectance Spectroscopy* and as a member of the technical review team for the Irish Critical Loads Program.

Joy M. Bergelson is Associate Professor in the Department of Ecology and Evolution at the University of Chicago. She graduated summa cum laude with a RI:ScB in Biology and obtained her master's and PhD from the University of York, UK and University of Washington, respectively. In 1993, she received the Young Investigator Award from the American Society of Naturalists and the Presidential Faculty Fellow Award. The research in her laboratory focuses primarily on the ecology and evolution of plant resistance traits. She and members of her laboratory combine ecological field experiments with transgenic manipulations to explore the fitness effects and selective histories of particular resistance genes. In addition, she maintains a broad interest in plant population biology and is involved in projects on weed invasiveness, plant population dynamics, plant quantitative genetics, and global environment change in natural and experimental systems.

Carol J. Fialkowski is conservation education director of the Field Museum of Natural History and an adjunct faculty member in science education at the National-Louis University, Chicago State University and Northeastern Illinois University. Before joining the Field Museum, she served as vice president for education exhibits at the Chicago Academy of Sciences. She obtained her BA in social science from St. Xavier

University and her MEd in environmental science from the National-Louis University. She has served on several education steering committees, including the National Biodiversity Educator's Network and the Biodiversity Project.

Dorothy M. Gibb is senior technical director of Horne Engineering Services, Inc. She received her PhD in botany from the University of Georgia and her MSc from the University of London, UK. Dr. Gibb has over 16 years of experience in environmental assessment, natural-resource management, policy analysis, research, analytical design, and project management and execution. The majority of her recent work has been supporting US Department of Defense headquarters organizations and individual military installations in ecosystem management and natural-resources management planning. She has been involved in review and development of natural resources policy and guidance, has been senior author of over 10 integrated natural-resources management plans, (INRMPs), and has recently completed a Web-published natural-resources management implementation handbook. Dr. Gibb also has experience with bioaccumulation, biogeochemistry, and ecological risk assessment.

John F. Heidelberg is assistant investigator at The Institute for Genomic Research. He served as principal investigator on the *Vibrio cholerae* genome sequencing project and is the principal investigator on the *Shewanella oneidensis (putrefaciens)*, *Dehalococcoides ethenogenes, Desulfovibrio vulgaris*, and T4-related Vibriophage KVP40 genome sequencing projects. He received his PhD from the University of Maryland, College Park in marine, estuarine, and environmental science.

Gretchen E. Hofmann is assistant professor at the University of California, Santa Barbara. She received her BA from the University of Wyoming, and MS and PhD from the University of Colorado, Boulder. Research in her laboratory focuses on the ecological physiology of marine animals, in particular intertidal invertebrates and perciform fishes. The four main research projects in the Hofmann laboratory are in ecological significance, expression, and function of heat-shock proteins as molecular chaperones, latitudinal gradients of thermal stress in the intertidal (are species more physiologically stressed at the extremes of their biogeographic range?), patterns of gene expression on a latitudinal scale in marine invertebrates, and evolutionary loss of stress-induced gene expression in Antarctic fishes.

Peter J. Hudson is Willaman Professor of Biology at Pennsylvania State University. His research interests include the examination of disease flows through wild animal populations, which individuals are important for transmission, the mechanisms that lead to persistence in the population, and the consequences of individual infections on host population dynamics. One of his long-term interests has been the sublethal effects of parasites and pathogens on fecundity and their destabilization of host population dynamics. His current work is extending into interspecific interactions between parasites and pathogens in rabbit populations in the UK and mouse populations in Italy.

Robert J. Huggett is vice president for research and graduate studies and professor at Michigan State University. From 1994 to 1997, he was the assistant administrator for research and development for the United States Environmental Protection Agency (EPA). Before that, he chaired the Department of Environmental Sciences of the Virginia Institute of Marine Sciences at the College of William and Mary. He has held several other environment related management positions there since 1972, including chairman of the Department of Ecology and Pollution and the Department of Chemical Oceanography in the School of Marine Sciences. He received a doctoral degree in marine science in 1977 from the College of William and Mary, where he also studied as an undergraduate, and a master's degree in marine chemistry in 1986 from the Scripps Institution of Oceanography in 1968.

Dennis P. Lettenmaier is a hydrologist in the Department of Civil and Environmental Engineering at the University of Washington, where he joined the faculty in 1976. In addition to his service at the University of Washington, he spent a year as visiting scientist at the US Geological Survey in Reston, VA (1985-1986) and was the Program Manager of the National Aeronautics and Space Administration's (NASA) Land Surface Hydrology Program at NASA headquarters in 1997-1998. He is a member and Fellow of the American Geophysical Union (AGU) and the American Meteorological Society (AMS), and a member of the American Water Resources Association and the American Society of Civil Engineers (ASCE). He was a recipient of ASCE's Huber Research Prize in 1990, and is the author of over 100 journal articles. He is currently Chief Editor of the AMS *Journal of Hydrometeorology*. Dr. Lettenmaier's research interests include hydroclimatology, surface-water hydrology, and geographic information systems and remote sensing.

Bobbi S. Low is professor of natural resources and associate director of the Population-Environment Dynamics Program at the University of Michigan. She received her BA in biology from the University of Louisville and her MA and PhD in evolutionary zoology from the University of Texas. Her research interests include evolutionary and behavioral ecology of wildlife species; resource control and reproductive success in vertebrates, including humans; parental strategies in vertebrates; desert ecology and management of arid lands; integration of evolutionary theory and resource management, and resources and reproductive variance.

Stephen R. Palumbi is a professor at Stanford University. He moved his laboratory from Harvard University in 2002. His research interests are widespread, and he has published on a variety of marine and terrestrial systems, including the genetics and evolution of sea urchins, whales, corals, sharks, spiders, shrimp, bryozoans, and butterflyfishes. He has also published extensively on uses of genetic techniques in evolutionary and systematic studies, larval ecology and dispersion, and mechanisms of reproductive isolation and their influence on patterns of speciation in marine systems. His book, *The Evolution Explosion: How Humans Cause Rapid Evolutionary Change* was published by Norton in 2001. He earned a PhD in Zoology in 1984 from the University of Washington and received a BA in Biology in 1978 from the Johns Hopkins University in Maryland. He was selected as a Pew Fellow in Marine Conservation in 1996.

Camille Parmesan is an assistant professor at the University of Texas, Austin. She received her PhD in zoology from the University of Texas. For the last several years, the focus of her work has been on current effects of climate change in the 20th century on wildlife. Her work on butterfly range shifts has been highlighted in many scientific and popular press reports, such as those in *Science*, *Science News*, the *New York Times*, the *London Times*, National Public Radio, and the recent BBC film series *State of the Planet* with David Attenborough. The intensification of global warming as an international issue led her into the interface of policy and science. Dr. Parmesan has given seminars in Washington, DC for the White House, government agencies, and such non-government organizations as the World Conservation Union (IUCN) and the World Wildlife Fund (WWF). As a lead author, she was involved in multiple aspects of the *Third Assessment Report* of the UN Intergovernmental Panel on Climate Change.

Herman H. Shugart, Jr. is the W.W. Corcoran Professor of Environmental Sciences and the director of the Global Environmental Change Program at the University of Virginia. He received his PhD in zoology from the University of Georgia in 1971 and worked for the next 13 years in Tennessee, eventually as a senior research scientist at Oak Ridge National Laboratory and as a professor in botany and the graduate program in ecology at the University of Tennessee. In 1984, he moved to his current position at the University of Virginia. Dr. Shugart has also served as a Visiting Fellow in the Australian National University (1978-1979 and 1993-1994), in Australia's Commonwealth Industrial and Scientific Research Organization (CSIRO), Division of Land Use Research (1982) and Division of Wildlife and Ecology (1993-1994), in the International Meteorological Institute at the University of Stockholm, Sweden (1984), and in the International Institute of Applied Systems Analysis, Laxenburg, Austria (1987 and 1989). He has served on the editorial boards of several scholarly journals including *Ecology* and *Ecological Monographs*, *Annual Reviews in Ecology and Systematics*, *Biological Conservation*, *Landscape Ecology*, *Journal of Vegetation Science*, *Forest Science*, *Global Change Biology* and *The Australian Journal of Botany*. He is the author of 254 publications, including 11 books, 60 book chapters, and 90 papers in peer-reviewed journals.

APPENDIX B

National Research Council Workshop on the National Ecological Observatory Network

AGENDA

Date: June 10, 2003
Location: The National Academy of Sciences Building, Washington, DC

1:30 – 1:40 p.m.	Introductions and description of the Web cast format G. David Tilman, University of Minnesota
1:40 – 2:40	Sponsoring agency's perspective on "The National Ecological Observatory Network" and the reason for this study Mary Clutter, Joann Roskoski and Sonya Mallinoff, National Science Foundation
2:40 – 3:45	Views of other relevant government agencies Abigail Miller, The National Park Service Jeffrey Frithsen, US Environmental Protection Agency Jerry Elwood, US Department of Energy Allen Dedrick, US Department of Agriculture—Agricultural Research Services Linda Gundersen, US Geological Survey

3:45 – 4:00	Break
4:00 – 5:00	Views of professional societies and organizations Kent Holsinger, American Institute of Biological Sciences Nadine Lymn, Ecological Society of America Anthony Janetos, The H. John Heinz Center for Science, Economics and the Environment Scott Miller, National Museum of Natural History Louis Pitelka, Association of Ecosystem Research Center (statement read by NRC staff)

Federal Agencies and Professional Societies that Voiced their Support for the National Ecological Observatory Network through the National Research Council Workshop and Web Forum

Federal agencies supporting the need for NEON:

National Park Service
United States Environmental Protection Agency
United States Department of Energy
United States Department of Agriculture – Agricultural Research Service
United States Geological Survey

Professional societies supporting the need for NEON:

American Institute of Biological Sciences
American Society of Mammologists
American Society of Parasitologists
Association of Ecosystem Research Centers
Ecological Society of America
H. John Heinz Center for Science Economics and the Environment

National Museum of Natural History
Natural Science Collections Alliance
Society for Integrative and Comparative Biology
Society of Nematologists

Plate 1 Location of AmeriFlux sites across the coterminous United States. Red dots represent the 52 AmeriFlux sites. SOURCE: modified after http://research.esd.ornl.gov/~hnw/networks/fluxdummy.f.png

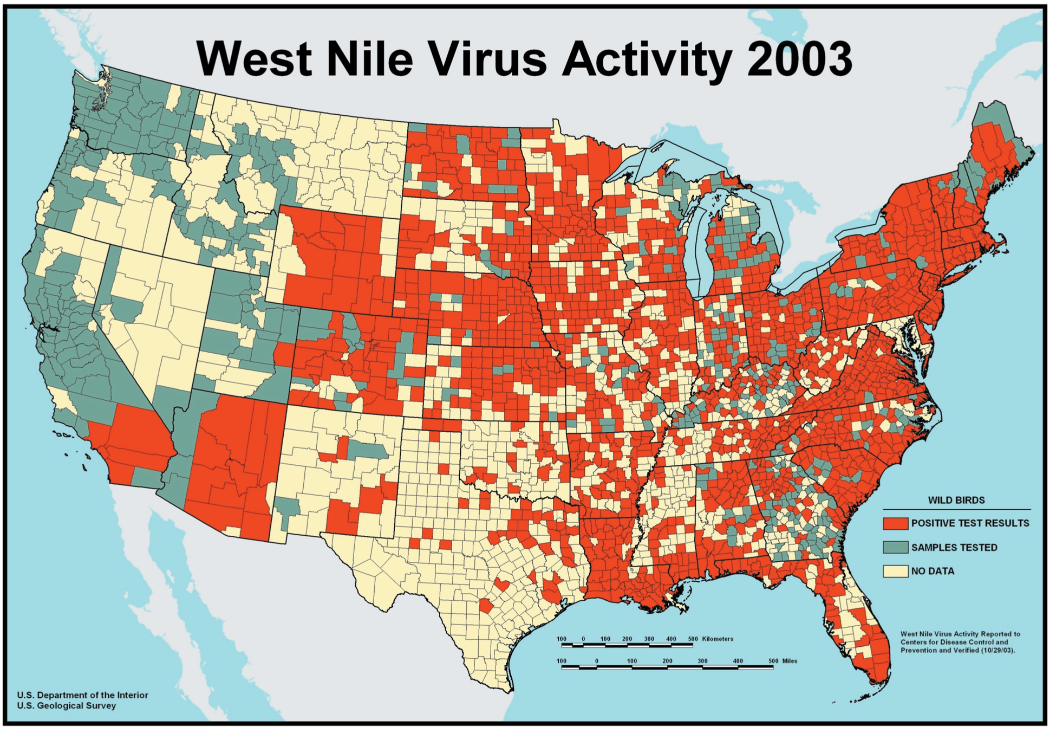

Plate 2 Map showing areas where wild birds have been tested positive for West Nile virus in the United States. SOURCE: http://westnilemaps.usgs.gov/usa_avian.html.

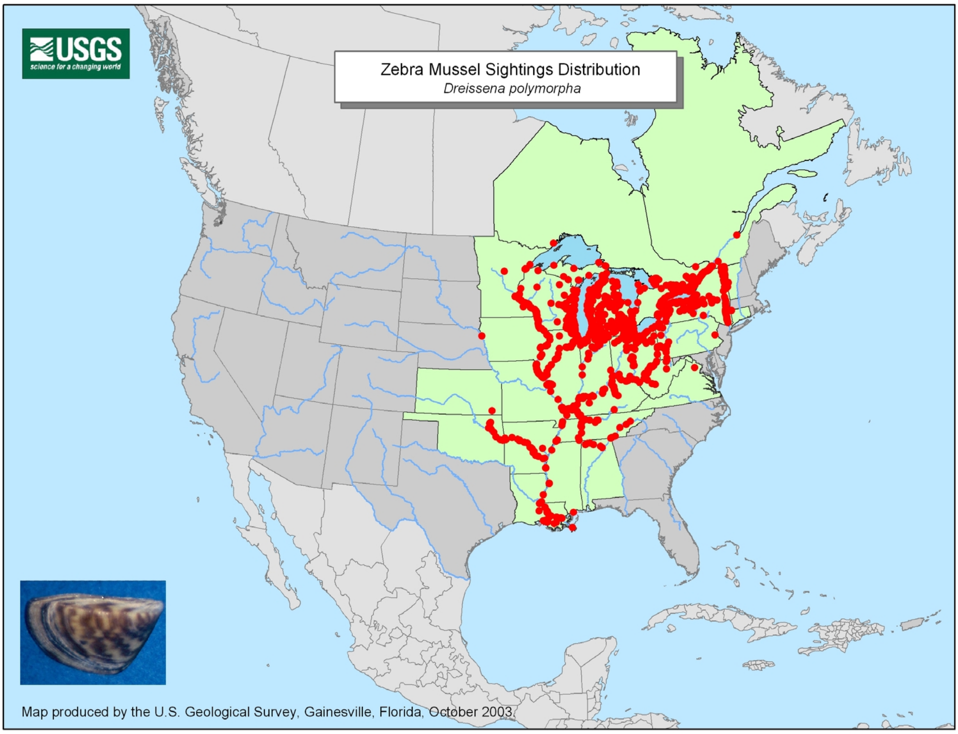

Plate 3 Map showing the extent of zebra mussel invasion in North America as of September 2002. SOURCE: http://nas.er.usgs.gov/mollusks/maps/current_zm_map.jpg.

Plate 4 Aerial photograph of the Aspen Free-Air Carbon Dioxide Enrichment (FACE) experimental site. The Aspen FACE experiment is a multidisciplinary study to assess the effects of increasing tropospheric ozone and carbon dioxide on aspen-forest ecosystems. SOURCE: http://aspenface.mtu.edu/.

Plate 5 Eddy covariance tower. The development of the eddy covariance method for measuring net carbon balances over short intervals has revolutionized ecosystem biogeochemical studies. Eddy covariance provides a new window into ecosystem function that increases our understanding of the processes and controls that determine element balances. SOURCE: http://harvardforest.fas.harvard.edu/.

Plate 6 Hubbard Brook Long-Term Ecological Research (LTER). Watershed 5 at Hubbard Brook LTER was whole-tree clear-cut from autumn 1983 through spring 1984. This watershed manipulation was designed to assess the effects of a commercial whole-tree harvest on nutrient cycles. SOURCE: http://www.hubbardbrook.org/research/gallery/aerial/W5.jpg.

Plate 7 Aerial photograph of plots for studying biodiversity at Cedar Creek Long-Term Ecological Research (LTER) site. Cedar Creek LTER, one of the longest-running biodiversity studies, began in 1994. SOURCE: David Tilman.